4.0 PROCESS CHEMISTRY

Learning Objectives

After studying this chapter, you should be able to:

1. Define and/or explain:
   a. Acid
   b. Base
   c. pH
   d. Conductivity
   e. Radiolytic dissociation/recombination of water
   f. Crud trap
   g. Crud burst
   h. Decontamination factor

2. Explain the operation of a voltaic cell, including the functions of the anode, cathode, and electrolyte.

3. Briefly describe the six basic forms of corrosion found in power plant piping systems.

4. Explain the basic crud cycle.

5. List the sources of radioactivity in light water reactors and give examples of radio nuclides that are associated with each source.

6. Explain the principles of ion exchangers, demineralizers, and ion affinity.

7. Explain the differences between deep bed and powdered-resin demineralization.

8. State and/or explain several chemistry measurements that are performed on PWR and BWR plant waters.

4.1 Acids and Bases

Many of the chemicals that are put into water solutions in the plant can be categorized as either acids or bases. When acids or bases are dissolved in water, they dissociate, forming cations (positively charged ions) and anions (negatively charged ions). (Recall from the Power Plant Engineering (PPE) Pre-Study Text that ions are atoms or groups of atoms with an excess of either positive or negative charges.)

When an acid dissolves in water, the cation formed is the hydrogen ion (H^+). Acids in a water solution always yield positively charged hydrogen cations along with counterpart negative anions. Because the hydrogen ion immediately forms an electrostatic bond with a water molecule, it is sometimes written as H_3O^+, and called the hydronium ion. Chemically, the two notations are equivalent; this chapter uses the H^+ notation. Therefore, when a sulfuric acid molecule (H_2SO_4) ionizes in water, it produces two hydrogen (H^+) cations and one sulfate (SO_4^{--}) anion.

$$H_2SO_4 \text{ (in water)} \rightarrow 2H^+ + SO_4^{--}$$

When a base dissolves in water, the anion formed is the hydroxide ion (OH^-), which is sometimes called the hydroxyl ion. Bases in a water solution always yield negatively charged hydroxide anions along with counterpart positive cations. Thus, the ionization of sodium hydroxide (NaOH) produces sodium (Na^+) cations and hydroxide (OH^-) anions.

$$NaOH \text{ (in water)} \rightarrow Na^+ + OH^-$$

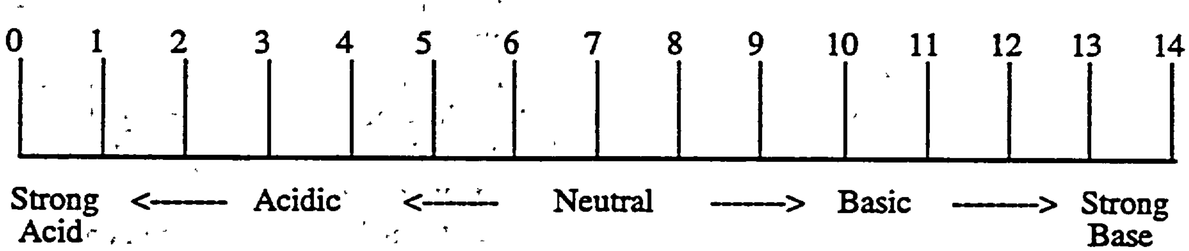
In neutral water the concentrations of hydrogen and hydroxide ions are equal; there is no excess of either ion. If the hydrogen ion concentration is greater than the hydroxide ion concentration, the solution is called an acid. If the hydroxide ion concentration is greater than the hydrogen ion concentration, the solution is called a base. This is a significant consideration in the plant because hydrogen and hydroxide ions in the plant waters affect the rate at which plant piping and components corrode. In extreme cases, strong acidic solutions and very strong basic solutions can rapidly cause metal damage through corrosive attack.

It is important to know whether the water in the plant is either a basic solution (also called alkaline) or an acidic solution, and to what degree the water is basic or acidic. It is possible to define how acidic or how alkaline a solution is by determining the concentration of the hydrogen ions or hydroxide ions in the solution. Because these ionic concentrations are normally very small, using negative powers of 10, the concept of the pH of the solution was developed. The pH of a solution is an inverse logarithmic measure of the concentration of hydrogen ions in the solution; therefore, the pH is an inverse measure of how acidic or alkaline the solution is. The definition of pH is the negative logarithm (to the base 10) of the hydrogen ion concentation (in moles/liter). (Recall that the bracket symbol is the notation for the concentration of a solute in solution in moles/liter.

$$pH = -\log [H^+] = -\log [H_3O^+]$$

The pH of a solution is measured on a scale numbered from zero to fourteen as shown below. On this scale, the strongest acidic solutions with very high concentrations of hydrogen ions have a pH approaching 0. As the concentration of hydrogen ions is *reduced* (by dilution with neutral water <u>or</u> by the addition of hydroxide ions), the pH *increases* and the pH measurement value moves up the scale. Up to a pH value of 7, a solution will be acidic. If the pH is greater than 7, the solution will be basic. The strongest basic solutions, with very high concentrations of hydroxide ions, have a pH approaching 14.

The pH Scale



In pure water a small amount of water dissociates into hydrogen and hydroxide ions in a reversible reaction as shown in Equation 4-1:

$$H_2O \Leftrightarrow H^+ + OH^- \tag{4-1}$$

Pure water at 25°C dissociates to form equal concentrations of hydrogen and hydroxide ions, each at 10^{-7} moles per liter. This hydrogen ion concentration yields a pH of 7. A solution with a pH of 7, at the midpoint of the scale, will have equal concentrations of hydrogen and hydroxide ions. At this point, the hydrogen cations and the hydroxide anions are balanced, and the solution is said to be <u>neutral</u>. Pure water is an example of a neutral solution.

Note that a solution with a pH of 7 does not have to be pure water. If ionic substances other than acids or bases, such as salts or minerals are present in the solution, the ions from these substances will increase the total ionic concentration of the solution without affecting the pH of the solution. If the solution is very pure water, however, and free of other ionic substances, the hydrogen and hydroxide ions produced by the dissociation reaction shown in equation 4-1 will produce a small but measurable total ionic concentration in the solution. This total ionic concentration will be about 2×10^{-7} moles/liter, which is a very small total ionic concentration. This pure water solution is often called demineralized water because there are no minerals or mineral salts present in the solution and the total ionic concentration is very small.

If sulfuric acid (H_2SO_4) is added to a pure water solution, the hydrogen ion concentration in the solution is increased (with a corresponding decrease in pH), and the total ionic concentration increased due to the increase in hydrogen ion concentration and the increase in sulfate ion concentration. Conversely, if the base sodium hydroxide (NaOH) is added to the pure water solution, the hydrogen ion concentration in the solution is decreased (with a corresponding increase in pH), but the total ionic concentration is increased due to the increase in hydroxide ion concentration and the increase in sodium ion concentration. In both cases, as the pH is changed farther away from 7 (either downward for an acid addition or upward for a base addition), the total ionic concentration of the solution increases.

The pH scale is a bit more complicated than it looks. Because it is a decade scale, a change of one number on the pH scale represents a change in the hydrogen ion concentration (and the hydroxide ion concentration) by a factor of ten. Therefore, a solution with a pH of 3 has a hydrogen ion concentration ten times greater than a solution with a pH of 4. The same relationship holds true for basic solutions. A solution with a pH of 12 has a hydroxide ion concentration that is one hundred times greater than a solution with a pH of 10. Table 4-1 shows the relative concentrations of hydrogen and hydroxide ions associated with specific values on the pH scale.

It is possible to measure the pH of a solution by measuring the voltage developed across a cell composed of two electrodes and the solution to be tested. The pH meter itself is actually a very sensitive voltmeter, with the readout scale calibrated in pH. One of the two electrodes used is a reference electrode, and the other is an electrode made of a special pH-sensitive glass. As the H+ ion concentration of the solution changes, the voltage developed between the glass electrode and the reference electrode also changes. The pH meter measures the voltage developed and reads out in pH.

As the temperature of the solution is increased above 25°C, the number of ions produced by the water dissociation reaction (Equation 4-1) increases, and the mobility of resultant ions also increases. Therefore, the pH of a neutral or near neutral solution is very sensitive to changes in the temperature of the solution. To take this factor into account during pH measurements, the temperature of the solution is measured, and a compensating dial on the pH meter is adjusted. Some pH measuring systems measure the temperature and compensate the meter circuit automatically. These automatic systems are generally used for the in-line pH meters that are installed in nuclear plants.

A pH meter is always calibrated with a solution of known pH to ensure that it is operating properly. The solutions used are called <u>buffer solutions</u> because they have the special characteristic of maintaining a constant pH over a range of concentrations and in the presence of small amounts of acidic or basic impurities. Whenever there is any doubt about a pH reading, the meter should be checked with a buffer solution that has a pH near the pH of the test solution.

4.2 Conductivity

The ability of a material to conduct electricity is called <u>conductance</u>. Solutions that contain ionized materials conduct electricity because the ions carry the electricity through the solution. The conductance of ionic solutions varies widely. One reason for the variation is that different ions have different mobilities (velocities) through the solution. The hydrogen ion has the greatest mobility, the hydroxide ion is next (having about half the mobility of the hydrogen ion), and all other ions have considerably less mobility. The more important cause of the variation in conductance between solutions is the variation in ionic concentrations. As the ionic concentrations in a solution increase, the conductance increases because there are more ions to carry the electricity.

The solutions in a power plant are usually dilute water solutions, which are very poor conductors of electricity. In comparison to metals (good conductors with a large number of free electrons), dilute water solutions have very few ions available to carry electricity. Under plant operating conditions, the flow of electricity through or across water systems is so limited that it is difficult to measure its conductance.

For situations in which very few ions are available to conduct electricity, we actually measure the resistance, or inability of the solution to carry or conduct electricity. Because conductance is the ability to conduct an electric current and resistance is the "inability" to conduct an electric current, these two concepts are inversely related, as shown in Equation 4-2:

$$\text{Conductance} \propto \frac{1}{\text{Resistance}} \tag{4-2}$$

Because resistance is commonly expressed in units of ohms, the unit mho (ohm spelled backwards) is used for conductance. The solutions generally found in the plant are very dilute, and the conductance is very low. Therefore, the conductance of solutions in the plant is usually expressed in terms of micromhos (10^{-6} mhos).

As with pH measurements, the conductance of a solution varies with temperature. For this reason, conductance is usually measured at a temperature of 25°C. This constant temperature measurement allows for comparing values from one conductance reading to the next or from one point in a system to another.

Because there are other variables that must be considered in measuring conductance, a specific set of measuring conditions has been established to ensure the validity of comparable readings. The conductance of a solution measured at 25°C between two electrodes that are each 1 cm^2 in area and are spaced 1 cm apart is called the specific conductance, or the <u>conductivity</u>. The units of conductivity are micromhos/cm (micromhos per cm^3 of solution per cm^2 of electrode).

The theoretical conductivity of pure water has been established at 0.054 micromhos/cm at 25°C. The conductivity of the water coming out of a plant makeup system will often approach this very low value. If a sample of the makeup system effluent is taken to the lab for analysis, its conductivity will probably be between 0.5 and 1.0 micromhos/cm. The increase occurs because the sample absorbs gaseous impurities from the air while it is being taken and carried to the lab, and while it is being measured. The only way to measure the conductivity of very pure water is to use an in-line conductivity measuring device. If the measuring device is actually in the line, it will measure only the impurities in the stream, not those absorbed after sampling.

As discussed in Section 4.1, the pH value of a solution is a measure of the acidity or hydrogen ion concentration (in moles/liter) in the solution. Similarly, the conductivity of a solution is a measure of the total concentration of dissolved ions in the solution. However, the conversion between the conductivity of a solution and the total ionic concentration of the solution is affected by many variables, including the percentages and mobilities of the various ions. Determination of the exact percentages of the various ions would require very sophisticated measurement methods. Therefore, an approximate conversion value based on the expected ion percentages is normally used, and the resultant total ionic concentration is expressed in parts per million or parts per billion. Since the actual ionic composition and ionic percentages of the solution are unknown, the resultant value is often called the concentration of total dissolved ions or total dissolved solids in the solution.

Because conductivity is a measure of the total dissolved ion concentration in a solution, the conductivity of acidic/basic solutions will be greatly affected by the pH of the solution. Section 4.1 explained that the total dissolved ion concentration of an acidic or basic solution increases as the pH varies farther from 7. Therefore, the conductivity of these solutions also increases as the pH varies farther from 7. When the identity of the acid or base in the solution is known, a proportionality constant between pH and conductivity can be determined and a curve of the expected conductivity versus the solution pH can be constructed. If the measured conductivity of a solution is significantly greater than the expected conductivity value for the measured solution pH, there must be other ionic impurities present in the solution that are responsible for the unexpected conductivity increase.

Conductivity measurements are used to determine the concentration of dissolved ions in all reactor plants, but the manner of usage varies slightly between BWR and PWR plants. In BWR plants the pH of the reactor feed water is kept as close to neutral as possible. Since the conductivity of pure water has been established, any significant increase in the conductivity of the feedwater above this value indicates either that ionic impurities have entered the feed system, or that the pH of the feed water has suddenly increased above, or decreased below, the neutral pH (7) of pure water.

On the other hand, PWR reactor coolant systems contain boric acid for reactivity control. Many PWR plants also use LiOH in the reactor coolant to maintain a slightly basic pH for corrosion control. PWR plants must measure the pH and boric acid concentrations in the coolant and plot these values on a standard curve to determine the expected conductivity. If the measured conductivity differs significantly from the expected value, it indicates that other ionic impurities are reaching the reactor coolant system.

4.3 Radiolysis of Water

The discussions of nuclear plant corrosion later in this chapter will highlight that dissolved oxygen in nuclear plant waters is a significant contributor to piping system corrosion. The one source of dissolved oxygen that is specific to nuclear power plants is the radiolysis of water. The oxygen atom that is bound with the two hydrogen atoms in a water molecule, or is bound with one hydrogen atom in a hydroxide ion, is not a significant corrosion problem. Oxygen is a significant corrosion problem when it exists as a free oxygen ion or is dissolved as a free oxygen molecule (O_2). Radiolysis is the dissociation of molecules by radiation, and the radiolysis of water molecules in the reactor core can be an important source of free oxygen in reactor coolant when the reactor is operating at power.

Under a strong neutron flux, such as in the reactor core at power, the hydrogen-oxygen bonds in the water molecules can be broken, and the molecules separated into the individual atoms. The chemical equation for this radiolysis or radiolytic dissociation of water can be written as follows:

Under neutron flux: $H_2O \rightarrow 2H + O$ (unbalanced)

The complete balanced reaction is shown in Equation 4-3:

Under neutron flux: $2H_2O \rightarrow 2H_2 + O_2$. (4-3)

Only a small percentage of the water molecules in the core undergo the dissociation reaction, but because there is a huge amount of water in the core, a significant amount of free oxygen is formed by this reaction.

With a strong gamma flux (as exists in the reactor core at power), a reverse radiolytic or recombination reaction will also occur, as shown in Equation 4-4:

Under gamma flux: $2H_2 + O_2 \rightarrow 2H_2O$. (4-4)

The recombination reaction may not go strongly enough to the right to remove all the free oxygen in the coolant unless it is somehow assisted. In BWR plants, the oxygen gas comes out of solution and leaves the core with the generated steam. The normal practice at PWR plants is to maintain an excess concentration of dissolved hydrogen in the reactor coolant when the coolant is at elevated temperatures and subject to strong gamma radiation. The hydrogen does not contribute to plant corrosion, but it does force the recombination reaction strongly to the right and thereby "scavenges" any available dissolved oxygen. (The chemical oxygen scavengers, like hydrazine, that are added when the coolant is cold, break down under high temperature and high flux and cannot remove the dissolved oxygen in an operating reactor core. PWR plants cannot stop the formation of dissolved oxygen by the dissociation reaction, but the maintenance of an excess hydrogen concentration in the coolant ensures that any dissolved oxygen formed by the dissociation reaction is promptly removed by the recombination reaction.

Hydrazine is added to the reactor coolant when the plant is at temperatures below 200° F and the reactor is shutdown. The addition of hydrazine results in the following reaction:

$$2O_2 + 2N_2H_4 \rightarrow 2N_2 + 4H_2O$$

For either hydrogen or hydrazine, as the chemical concentration in the coolant is increased, the scavenging reaction is driven more strongly to the right, and oxygen is removed from solution. This is a desirable condition because the concentration of oxygen in the coolant directly affects the amount of system corrosion experienced.

4.4 Voltaic Cells

The voltaic cell or galvanic cell typically consists of two bars or plates of dissimilar materials immersed in an electrolytic (or ionic) solution. Because this arrangement can produce a voltage potential between the two bars, the bars are known as electrodes, with the positive electrode called a cathode and the negative an anode. (The electrodes can have any shape, but they are normally shown as bars.) Copper and zinc are frequently used as electrodes. The electrolyte normally consists of a water solution of an acid, base, or salt that is strongly ionized in water. A sulfuric acid (H_2SO_4) solution is used as the electrolyte in the simple voltaic cell shown in Figure 4-1.

As sulfuric acid dissolves in water, complete ionization occurs; the acid rapidly dissociates into hydrogen ions (H^+) having a single positive charge and sulfate ions carrying two negative charges (SO_4^{--}).

If a zinc electrode is immersed in the acid solution, some of the zinc will corrode or undergo oxidation. In corroding, zinc ions containing two positive charges (Zn^{++}) leave the electrode and pass into the electrolyte. Each zinc ion that goes into the solution leaves two electrons behind, causing a negative charge to accumulate on the zinc electrode. As the zinc electrode becomes negative, it attracts the positive ions in the solution, causing some of the zinc ions to return to the electrode. In a short time, an equilibrium is established and the rate of loss of ions from the zinc is equal to the rate of ion return. The zinc electrode remains negative and a cloud of positive ions forms in the nearby electrolyte.

When a copper bar is also immersed in the acid solution, some of the positive hydrogen ions (H^+) in the electrolyte contact the surface of the copper. Each positive ion then pulls one of the many free electrons out of the copper and becomes a neutral atom of hydrogen gas. The copper electrode, which has given up its electrons to the hydrogen ions, accumulates a positive charge and a blanket of hydrogen gas.

The chemical equations for the reactions that occur at the electrodes of the voltaic cell shown in Figure 4-1 are:

Zn (in electrode) $\rightarrow Zn^{++}$ (goes into solution) $+ 2e^-$ (accumulate on electrode), and

$2H^+$ (in solution) $+ 2e^-$ (on electrode) $\rightarrow H_2$ (accumulates on electrode).

As a consequence of the above chemical action, the zinc electrode becomes negative and the copper electrode becomes positive. Therefore, a voltage difference, or potential, is created between the two electrode terminals, and the cell is capable of supplying electrical energy to an external electrical circuit that can be connected between the two terminals. A voltaic cell constructed with copper and zinc electrodes will develop a potential between the electrode terminals of about 1.08 volts.

After an external conductor has been connected, the electrodes become the conductors by which the current leaves or returns to the electrolyte. In the example voltaic cell, the electrodes are copper and zinc rods that are immersed in the electrolyte; in the dry cell (flashlight "battery"), the electrodes are the carbon rod in the center and the zinc container in which the cell is assembled.

The electrolyte is the solution that acts upon the electrodes which are immersed in it, and completes the electrical circuit by allowing electron flow (through ion transport) between the electrodes. The electrolyte may be a salt, an acid, or an alkaline solution. In the simple galvanic cell and in the lead-acid storage battery, the electrolyte is in a liquid form; in the dry cell, the electrolyte is a paste.

The electrodes of a voltaic cell are often referred to in other terms. The negative electrode from which electrons leave the cell to flow to the external circuit is called the anode. The positive electrode into which electrons flow from the external circuit is called the cathode.

4.5 Corrosion

Uncontrolled corrosion in a nuclear power plant can cause many serious problems. Corrosion occurs continuously in the plant, and every metal in the plant is subject to some type of corrosion. If corrosion is allowed to become excessive, the following types of problems can occur:

- As corrosion products are carried into the core and build up on core surfaces, the water channels become smaller and the core pressure differential increases. The resultant flow decrease may force the plant to reduce the total power output of the reactor.
- The buildup of corrosion deposits on fuel surfaces will decrease the rate of heat transfer from the fuel to the water. As a result the fuel can overheat, and fuel cladding failures may occur.
- Increased activated corrosion product levels in the coolant may increase plant radiation levels and eventually overload the waste disposal system.
- Increased corrosion may cause fuel cladding breaches which will increase fission product concentration in the coolant.
- Piping failures may occur in the coolant system.
- Failure caused by corrosion may result in a release of radioactivity inside the plant.

Even though corrosion in the plant cannot be eliminated, it can be controlled to prevent the adverse consequences listed above. For this reason, it is important to understand the reason that corrosion occurs and the steps that can be taken to control corrosion effects.

In simple terms, corrosion is the action of a metal trying to return to its natural state. In the natural state, a metal exists as a metal oxide. Metal ores are refined before they are used in the manufacture of plant components. The refining process reduces the metal oxides that are part of the natural metal ores and produces pure metal. During corrosion, the refined or pure metal is oxidized to return to its natural or oxide state.

4.5.1 Corrosion of Iron

Many of the systems and components in the plant are made from iron. When iron corrodes, it is trying to return to its natural state by forming iron oxides, which we normally see as red rust. In nuclear systems the corrosion of iron does not

not always form red rust because there are other factors involved in the corrosion process.

Corrosion is an electrochemical process; that is, it involves both electricity and chemistry. Because of some difference in materials or environment between two locations, an anode and a cathode are formed on an iron surface that is exposed to an ionic solution. The solution conducts electron flow like the electrolyte in a voltaic cell. A voltage potential will be created to cause electrons to flow through the iron from the anode to the cathode. A complete circuit is formed and electron flow continues while the anode is corroding.

Figure 4-2 illustrates the corrosion of iron. The figure has been drawn to indicate reactions that take place on a very small scale. The anode and cathode in these reactions may be adjacent iron grains. The metallic iron atoms at the anode are in equilibrium with iron ions in the electrolyte (water) at the anode. Some of the iron ions in solution at the anode combine with the hydroxide ions in the water to form a low-stability, transitional-state of ferrous hydroxide, $Fe(OH)_2$. An equilibrium conditon also exists between the iron ions in solution and the iron ions that are combined with the hydroxide ions.

The concentration of ferrous hydroxide in the electrolyte is directly affected by the concentration of dissolved oxygen in the solution. Oxygen promptly oxidizes the ferrous hydroxide and forms Fe_2O_3 (rust), which plates out on the iron surface. When the ferrous hydroxide is oxidized by the oxygen in the solution, and thereby removed from the electrolyte, additional iron atoms must be removed from the metal and converted to iron ions to maintain the ionic equilibria. The presence of dissolved oxygen, therefore, accelerates the removal of iron atoms from the metallic surface and accelerates the corrosion process.

Figure 4-2 also contrasts the sequence of events discussed in the above paragraph with the case where there is no dissolved oxygen present in the solution. In the latter case, when the iron ions enter the water, two free electrons are released to move through the metal from the anode to the cathode. At the cathode, the electrons combine with positively charged hydrogen ions from the water to form hydrogen gas molecules. The hydrogen gas forms a blanket at the cathode.

Once again the iron ions react with hydroxide ions in the solution to form the low-stability, transitional ferrous hydroxide $Fe(OH)_2$. If no dissolved oxygen is present, the ferrous hydroxide molecules will slowly coalesce and form a new material, Fe_3O_4 (called magnetite), that tends to plate out on the iron surface.

As the corrosion of the iron continues, the oxide that forms at the anode and the hydrogen gas that forms at the cathode act as electrical insulators and resist the flow of ions. Thus, when an iron surface becomes covered with oxide film, the corrosion film serves as a barrier to slow down additional corrosion. Common red rust (Fe_2O_3) is porous, however, and quickly flakes off to expose fresh metal. At the cathode, the hydrogen gas that is formed normally coalesces to escape as bubbles, thereby removing the hydrogen gas layer that had acted to prevent additional corrosion.

If there is no dissolved oxygen in the water and the water temperature is kept high like the coolant in a nuclear plant, the magnetite produced at the anode will form a dense, protective oxide film on the iron surfaces. This film of black iron oxide (magnetite) is very adherent at high temperature if a slightly basic pH can be maintained in the coolant. Therefore, it acts as a good barrier against further corrosion. Modern nuclear plants follow special procedures to form this type of oxide film early in plant life. PWR plants also maintain the pH of the reactor coolant slightly basic to promote the adherence of the magnetite film at high temperatures.

Having some dissolved oxygen in the coolant is often unavoidable, especially during refuelings. Therefore, coolant piping surfaces are normally made of or clad with stainless steel. Stainless steel alloys contain chromium and exhibit enhanced general corrosion resistance due to the formation of a protective chromium oxide film by the following oxidation process:

$$4Cr + 3O_2 \rightarrow 2Cr_2O_3$$

This chromic oxide film is not impervious to penetration at the high temperatures used in reactor plants, but it does assist the magnetite film in retarding additional corrosion.

4.5.2 Corrosion Rate

The actual rates at which corrosion occurs in the plant are affected by a number of different factors. For example, it has been shown that a protective oxide film can slow down the corrosion rate of a metal surface. However, the flow of water past the metal surface can prevent the formation of a good oxide coating. When the water velocity is extremely high, the impact of the water can remove the oxide layer, thus exposing more fresh metal to corrosion. Water velocity can be considered a problem when it increases beyond approximately 30 to 40 feet per second.

Water temperature can also affect the rate at which corrosion proceeds. In general, chemical reactions proceed faster at high temperatures, and this is true of the oxidizing of metals. Water temperatures are usually high in the plant, and they must be considered as a factor that tends to accelerate the corrosion of plant materials.

Another factor that affects the corrosion rate is pH. This can be controlled in some cases by keeping the pH of plant water somewhere between neutral and slightly alkaline to maintain the adherence of the protective oxide layer described in the previous section.

Two other factors that can be controlled are dissolved oxygen and dissolved solids/ions in the plant water. High dissolved oxygen levels greatly accelerate the corrosion process, as described in Section 4.5.1. If dissolved ions are kept to a minimum, the ability of the water to conduct a current will be greatly reduced and the rate of the electrochemical process corrosion will be decreased.

4.6 Types of Corrosion

Corrosion can take place under a number of different circumstances, and the effects that the basic process causes can also be different. The most common type of corrosion is uniform corrosion, the general oxidation of a metal surface by the processes described in Section 4.5.1. Uniform corrosion takes place very slowly and produces an even oxide coating over the surface of the metal. The anodes and the cathodes are usually very close together and cannot be distinguished. The metal surfaces in the reactor coolant piping normally undergo very slow uniform corrosion. The small metal loss that occurs is allowed for in the plant design.

A more serious type of corrosion in the plant is crevice corrosion, which can occur in or near a crevice in a metal surface. Crevice corrosion takes place where there is a difference in the concentration of some material between the general environment and the crevice area. The concentration differences can occur in coolant systems because the flow through the crevice area is very restricted or nonexistent. When a material in the metal or the conducting solution (dissolved oxygen, metal ions, or other ions) is deficient in a relatively small, restricted area, but present in the remaining areas, the net effect is the formation of an anode in the deficient area and the rapid onset of localized corrosion. Figure 4-3 is a simplified drawing of the initial stages of crevice corrosion. Figure 4-4 shows some of the factors affecting crevice corrosion.

Pitting corrosion is similar to crevice corrosion. The main difference is that pitting can begin on almost any metal surface. It does not require the existence of a pre-existing flaw or other area of restricted flow. Pitting is a localized attack that occurs in the form of holes that are about as wide as they are deep. As corrosion products accumulate in these holes, the pits become, in essence, a form of crevice corrosion. As with crevice corrosion, pitting requires a difference in the makeup of the metal or the conducting solution (dissolved oxygen, metal ions, or other ions). Most pitting is caused by chloride and chloride-containing ions or by differences in dissolved oxygen concentrations. Pitting can cause rapid metal failure in pitted locations even though the remainder of the metal component is unaffected. Figure 4-5 illustrates some example types of pitting corrosion.

Crevice corrosion and pitting are of particular concern because they can occur almost anywhere in the plant. A third type of specific attack, galvanic corrosion, only occurs when two dissimilar metals are in contact in a conductive solution. Galvanic corrosion uses the same electrochemical processes that have been previoulsy described for general corrosion, but in this case separate components made of different metals or alloys are involved, rather than just small localized areas on the same metal surface. Galvanic corrosion may occur where heat exchanger tubes are welded to the tubesheets, or where two components with different alloy compositions are welded together.

In galvanic corrosion the weld area forms a good path for the flow of electrons between the two metals. The component made of the metal or alloy that has less corrosion resistance will become the anode, and the component made of the metal with more corrosion resistance will become the cathode. The severity of the corrosion will be determined by the potential (voltage) that is developed between the two metals, and this, in turn, will depend on the specific metals that are involved. Figure 4-6 shows galvanic corrosion between zinc and copper electrodes with seawater as the electrolyte.

The severity of attack that occurs as a result of galvanic corrosion is affected by the environment (including solution temperature and rate of flow) and the area ratio between the two metals involved. In general, the other metals in the environment will determine which metal is the anode and which is the cathode. Thus, the metal that is less corrosion resistant in a specific environment will be the anode, but this same metal in another environment might be the cathode. The size of the anode with respect to the cathode will determine the electric current density at the anode and, the amount of metal lost per unit area. If the cathode is much larger than the anode, the attack at the anode will be severe. If the anode is larger than the cathode, the attack will be less serious because the corrosion is spread over a much larger area.

One way to combat galvanic corrosion is to place an electrical insulating material between the two metals involved (do not weld them together). Another way is to use two metals that are very close to each other in their degree of corrosion resistance. The tendency toward a galvanic reaction is much less when the two metals used are similar in their resistance to corrosion. Reducing the conductance of the solution that contacts the metals will also help to slow down galvanic corrosion.

In some instances, galvanic corrosion of plant materials can be controlled by using *sacrificial anodes*. For example, zinc bars may be mounted in a seawater heat exchanger to protect the heat exchanger from corrosion. The zinc will become the anode and will corrode; the heat exchanger metal will become the cathode, and it will not be affected by the corrosion. This technique is also known as cathodic protection. The metal to be protected is forced to become a cathode, and it will corrode at a much slower rate than the sacrificial anode.

Another type of corrosion that can be a real problem in the plant is intergranular corrosion, which takes place in the areas between the grains of a metal (see Figure 4-7). When a metal is manufactured, it is cooled from a liquid state to a solid state. As it solidifies, the metal forms millions of tiny crystals or grains. The point at which two grains meet is called a grain boundary. In general, grain boundaries are more active chemically than the grains, and the grain boundaries usually corrode sooner and more rapidly.

Intergranular corrosion is usually the result of some chemical difference between the grain boundaries and the grains of the metal. The composition of the solution that contacts the metal also has a significant effect on the rate of attack. Intergranular corrosion begins on the surface of the metal, where the grains and the grain boundaries involved are in contact with the conducting solution. Once it starts, this type of corrosion can spread rapidly through the metal along the grain boundaries. Even though the actual loss of metal is relatively small, the whole structure of the metal can be weakened, and failure can occur very rapidly.

Intergranular corrosion is of particular concern for some cast and welded stainless steel components. Under certain conditions, some stainless steels that have been subjected to the high heat input of welding or stress relief become sensitized. Sensitization refers to the precipitation of chromium atoms as chromium carbides at the grain boundaries. The precipitated chromimum atoms are no longer available to form the protective chromic oxide film, and the associated grain boundaries are then subject to accelerated corrosion attack.

Stress corrosion cracking, like intergranular corrosion, can cause metal failure with relatively little metal loss. The stress involved is normally tensile stress, caused by bending or rolling the metal or by containing high system pressure. Stress corrosion cracking may attack along the grain boundaries in the metal, or it can cut across the grains. Because it can be extremely rapid under the right conditions, stress corrosion cracking is the most serious type of corrosion discussed in this section.

Much of the piping in reactor plants carries fluid under high pressure, and much of the piping is either bent or rolled, like tubing. Therefore, most of the piping in a reactor plant is susceptible to stress corrosion cracking. Although much testing has been done on stress corrosion cracking, the root causes of this type of corrosion are still unclear. It is known, however, that even very small concentrations (.15 ppm) of chloride or fluoride ions in the presence of dissolved oxygen will significantly increase the incidence of stress corrosion cracking. The prevention of stress corrosion cracking is the basis for the very stringent requirements (Technical Specifications) maintained by all nuclear plants on chloride ions in the coolant. If there are absolutely no chloride ions in the coolant, normal stress corrosion cracking will not occur. PWR plants also have stringent limits on fluoride ions and dissolved oxygen in the coolant because these impurities promote stress corrosion cracking. In BWR plants the fluoride and oxygen impurities are removed by the boiling process; BWRs try to maintain low levels of these impurities in the makeup water and feedwater.

4.7 Crud

Crud is a colloquial term for corrosion and wear products (rust particles, etc.) in the coolant that become radioactive when exposed to radiation. The term is actually an acronym for Chalk River Unidentified Deposits, named for the Canadian plant at which the activated deposits were first identified. Crud may be defined as deposited or suspended circulating corrosion products, principally metal oxides, formed by the reaction of water with piping materials. The term crud includes both radioactive corrosion products and nonradioactive corrosion products. Crud takes on special significance in nuclear plants because a large portion of it is radioactive.

The formation, transportation, and deposition of crud can be described in a sequence of six steps, which is called the crud cycle:

1. Corrosion products form and build up on out-of-core metal surfaces.

2. Part of the corrosion film that builds up on these surfaces is released into the circulating coolant where it is carried as a suspended impurity.

3. The corrosion products redeposit on other surfaces, frequently on the fuel surfaces in the core.

4. Corrosion products that have deposited in the core are activated by the intense radiation with the degree of activity depending in part upon how long the corrosion products remain in the core.

5. Some of the activated corrosion products are released from the core and are circulated in the reactor coolant, again as a suspended impurity.

6. The activated corrosion products may be redeposited on out-of-core surfaces and collected in low velocity crud traps.

In a BWR, much of the activated corrosion products are removed by the reactor water cleanup system while a small fraction may be carried off by the steam, thus contaminating the steam separators and the steam dryers. In a PWR, some of the crud is carried into the chemical and volume control system (CVCS) for removal from the primary system.

There is really no end to the crud cycle. Deposited material can be released again and carried back to the core surfaces, and the cycle will continue. Crud tends to deposit on plant surfaces because the crud particles tend to build up an electrical charge on them and so do the metal surfaces. If the two charges are the same, the crud particle is repelled and will not deposit. If the two charges are opposite, the crud particle will be attracted to the metal surface, and will tend to deposit.

Even though the crud cycle cannot be stopped completely, it can be slowed down. General corrosion of metal surfaces is slowed down by maintaining the protective oxide film described in Section 4.5.1. Circulating crud should be removed by filtration in the reactor water cleanup system (BWR) or chemical and volume control system (PWR).

Crud can have a number of adverse effects on the plant and its components. These can include the following:

- Mechanical fouling of equipment that has small clearances.
- Increase in the pressure drop across the core, which could cause a reduction in reactor flow that would require or produce a corresponding reduction in reactor power.
- High after-shutdown radiation levels as a result of the activated corrosion products being deposited on system surfaces.
- The discharge of radioactive corrosion products to the environment.

The potential adverse effects of crud must be considered when a nuclear plant is designed. The designer must select materials that minimize corrosion and deposition, allow for efficient removal of corrosion products with the purification system, design and arrange equipment to minimize crud deposition, and select coolant chemistry to reduce corrosion.

Because crud is a mixture of corrosion and wear products (rust particles, etc.) that have become radioactive when exposed to radiation, the radioactivity of the crud depends on several parameters. Included in the parameters that affect the radioactivity of crud are the length of time the corrosion and wear products spend in the core, the amount of crud present, the time that has passed since the crud was activated, and the activated metal species of the crud's component atoms. One component of crud that is especially important is cobalt-60 (Co-60), which emits relatively high level radiation upon decay and is present for long periods of time once produced.

Normal plant arrangements include many built-in crud traps. A crud trap is a low-velocity area where crud carried by the coolant stream can settle out and concentrate. The severity of the crud trap problem depends upon how radioactive the crud is (in general, the longer the crud is deposited in the core area, the more radioactive it will be upon release) and how much crud tends to concentrate in the trap. Some typical crud trap locations in the plant are:

- Instrument lines (particularly D/P cells)
- Valves (especially if they are installed with bonnets sloped down),
- Pump volutes,
- Heat exchanger heads,
- Vent and drain fittings,
- Test connections,
- Socket-welded fittings,
- Check valves,
- Connections of an auxiliary system to a main system,
- Thermal sleeves,
- Bypass lines,
- Relief valves,
- Handholes or manways, and
- Sampling lines.

The amount of of crud deposited on equipment surfaces is a function of (among other things) the concentration, electric charge, and solubility of the crud particles in the coolant, the velocity of the coolant in the area of the deposition, the physical shape of the component on which deposition is occurring, and the type of material on which deposition is occurring. Crud is continually released and redeposited on reactor coolant piping surfaces. Crud is less easily released from crud traps than from other piping surfaces where fluid velocity may be higher or the physical shape of the surface may be different. The lower release rates of crud from crud traps will result in thicker deposition layers in the crud traps than on other piping surfaces. Because the amount of activity in an area is proportional to the amount of crud present, the activity level experienced from a crud trap is higher than the activity level of other piping surfaces.

Crud traps cause localized areas of high radiation, which may complicate work in these areas. The problem can be reduced by making provisions for local flushing and decontamination, or by using extra shielding. To prevent these problems, the plant should be designed to have as few crud traps as possible. Proper design and positioning of components may significantly reduce the amount of crud that is trapped.

Problems in the plant may also occur as a result of crud bursts. A crud burst occurs when many crud particles that have been deposited on piping surfaces are jarred loose to circulate with the coolant as a result of some disturbance. Changing coolant flow rates can loosen crud particles, as can thermal shocks created by heatups and cooldowns. Other types of disturbances which could cause a crud burst are physical shocks, such as a reactor scram, or a chemical shock, such as the adding of hydrogen peroxide to the system before refueling.

When a crud burst occurs, crud may plate out on the fuel cladding, where the resulting poor heat transfer capabilities could cause the fuel to overheat. This could, in turn, lead to cladding failures and shorter fuel life. In addition, crud that is deposited on plant surfaces following a crud burst can be released again if it does not adhere tightly.

Thus, following a crud burst, the amount of crud available for additional release and deposit increases.

4.8 Sources of Radioactivity in Reactor Coolant

The following sections discuss the major sources of the radioactivity found in light water reactors.

4.8.1 Activation of Corrosion Products

As previously discussed in Section 4.7, corrosion products can become activated when they are exposed to high levels of neutron radiation in the core. The activated corrosion products can lead to radiation hazards and can directly affect the safety and efficiency of plant operations.

Activation occurs when corrosion products are carried into the core by the reactor coolant. In addition, the fuel cladding and other core components are already radioactive, and they release corrosion products into the reactor water when they corrode. Table 4-2 lists some of the more common activated corrosion products with their half-lives and formation mechanisms.

One of the isotopes listed in the table is Co-60. Cobalt, which exists naturally as Co-59, is widely used in the plant in various alloys for turbine blade tips, valve seats, and some control rod drive mechanisms. There are also traces of cobalt in most stainless steels. If Co-59 is activated by a neutron in the reactor, it becomes radioactive Co-60 by the following radiation reaction:

$$Co^{59}\ (n, \gamma)\ Co^{60}\ .$$

The reaction which produces Co-60 from Co-59 is not a chemical reaction like the combining of hydrogen and oxygen to form water. Instead, it is a radiation reaction, a reaction that occurs as a result of radiation interacting with atoms. A radiation reaction can produce a new isotope of the same element (Co-60 from Co-59), or it can change one element into another, as will be shown later.

Cobalt-60 is a potential problem in isolated or shut-down equipment. It has a relatively long half-life (about 5.2 years), and emits two high energy gammas (one 1.17 Mev and one 1.3 Mev). It also emits beta radiation. The emission of a particle (an alpha, a beta, or a proton) means that the product nuclide is a new element.

Cobalt-58 is a radiation product of nickel-58, which is found in all of the nickel-bearing alloys used in the plant. The radiation reaction is written as follows:

$$Ni^{58}\ (n, p)\ Co^{58}\ .$$

In this reaction, nickel-58, the target nuclide, is bombarded by a neutron. The particle emitted is a proton (symbol letter p), and the product nuclide is Co-58. Cobalt-58, with a half-life of 71.4 days, can be a problem especially during the first few years of plant life.

The most prominent nonradioactive corrosion product in the plant is iron because much of the plant equipment and piping is made of iron. Iron-58 is activated by the following radiation reaction:

$$Fe^{58}\ (n, \gamma)\ Fe^{59}\ .$$

Iron-59 has a half-life of 45.1 days and emits either a 1.10 Mev gamma or a 1.29 Mev gamma plus beta radiation.

The specific corrosion products that are important in an individual plant will depend upon the metal alloys used in the systems that handle the water going into the reactor. The activation products listed in table 4-2 are among the most common seen in the plants.

4.8.2 Activation of Water

In addition to the corrosion products that can be activated in the core, the plant water may also be activated by the neutron radiation in the core. The oxygen in the water may become activated and form many radioactive nuclides. The water does not remain in the core very long at any one time, but the large number of water molecules passing through the core means that, statistically, some will be activated.

The most abundant isotope of oxygen is oxygen-16 (O-16). Neutron activation of O-16 forms nitrogen-16 (N-16), and proton activation of O-16 forms nitrogen-13 (N-13). Of these two products, there is far more N-16 because more neutrons than protons are available to activate the O-16 in the water.

N-16 is the most abundant activation product in the reactor core. It has an extremely high gamma decay energy (6.13 Mev), and is the most limiting radionuclide for shielding that is installed around any equipment that carries reactor coolant.

For a BWR, this restriction also applies to any equipment that carries steam from the reactor. Because N-16 decays very rapidly (half-life of 7.13 seconds), it does not contribute to radiation levels after shutdown or after a portion of the system has been isolated. N-13, on the other hand, has a half-life of 10 minutes, and it does contribute to the gaseous activity of the plant.

Oxygen may also exist in plant water as O-17 or O-18. When these isotopes are activated, they create radionuclides such as nitrogen-17 (N-17), fluorine-18 (F-18), and O-19, but the amounts produced are very small in comparison with N-16. N-17 has a very short half-life (4.14 seconds), so it decays very rapidly after shutdown or system isolation. O-19 has a half-life of 26.8 seconds, and it does not cause significant problems. F-18 has a relatively long half-life, 109.8 minutes, and becomes significant after the decay of the shorter-lived activation products.

4.8.3 Activation of Water Impurities

In addition to the water molecules, the reactor coolant also contains trace impurities that may be activated as the water passes through the core. Of the impurities in water that may become activated, the most common are sodium and potassium. Sodium is activated to sodium-24, which has a high-energy gamma and can produce significant radiation levels for relatively long periods of time. Potassium is activated to form either of two nuclides, potassium-39 and potassium-41. Another element, argon, can become a radiation factor if there is air leakage into one of the water systems leading to the reactor. Argon, which occurs naturally in air, can become activated to argon-41.

Although it is normally found only in very small concentrations in a nuclear plant, tritium is an isotope of concern as a radiation hazard. The tritium isotope (hydrogen isotope with one proton and two neutrons) is not really an external hazard due to the very low energy of the emitted beta particle. However, it is a very significant ingestion hazard. Tritium will replace the normal hydrogen in water molecules to form tritium oxide. If the tritium oxide is then inhaled, the tritium will replace the hydrogen in the walls of the lungs, and the beta particle which is emitted can cause severe damage to the lung tissue. The radioactive half-life of tritium is 12.33 years.

There are four production mechanisms of tritium in a pressurized water reactor. First is a ternary fission. This is a fission in which there are two fission fragments and a tritium. If it is assumed that 0.1% of the tritium enters the coolant, ternary fission contributes about 40 curies per year to coolant activity.

A second source of tritium is the activation of deuterium (hydrogen isotope with one proton and one neutron). When deuterium absorbs a neutron, it converts to tritium. Since deuterium is such a small part of naturally occurring hydrogen, this source contributes only about 10 curies a year to the tritium activity.

The third source of tritium is from a lithium-6 isotope absorbing a thermal neutron to yield a tritium and a helium. To minimize the amount of tritium produced by this reaction, the lithium used in the lithium hydroxide pH additive is enriched to about 99.9% lithium-7. This reaction contributes about 17 curies per year to the tritium activity.

The fourth and major contributor to tritium activity is the absorption of a greater than or equal to 1.5 Mev neutron by a boron-10 atom. When this occurs, the boron-10 breaks down into a tritium and two helium particles. This contributes about 90% of the yearly production of tritium, or about 560 curies per year. The total yearly production of tritium for a PWR is about 627 curies per year.

For a BWR, the amount of tritium produced is considerably less than a PWR. This is because the BWR does not use boron for reactivity control during normal operations, and it does not use lithium hydroxide for pH control. Therefore, the only contributors to tritium production in a BWR would be . :nary fission and the absorption of a neutron by a deuterium atom.

4.8.4 Fission Products

Another source of radioactive material in the plant is the fission products that are released during the fission process, primarily from the fissioning of uranium-235 and plutonium-239. Fission products are often grouped into three categories:

- Iodines, particularly iodine-131 and iodine-133 (see Table 4-3).
- Fission gases — kryptons and xenons, particularly krypton-85 and xenon-133 (see Table 4-4).
- Soluble metal ions, particularly strontium-90 and cesi"m-1:7 (see Table 4-5).

Fission products get into the reactor water in two ways. First, they could be released from tramp uranium in the fuel cladding. This means that there may be some fuel residue on the outside of the fuel cladding that was left there during the fuel fabrication process. When this fuel fissions, the fission fragments will be in direct contact with the water. Also, the Zircaloy cladding usually contains trace amounts of uranium as an impurity. This fuel, if it is close enough to the surface, will release its fission products with enough kinetic energy to get to the surface of the cladding and then into the reactor water. Figure 4-8 shows that for the fission fragments to make it to the coolant they must be within the recoil range (recoil is the ejection of the fission fragments after fissioning). If the fragments are within 7 to 11 microns of the cladding surface, they will have a good chance of making it to the coolant.

The second way for fission products to get into the coolant is through a defect in the cladding. In this case, it is possible for fission fragments produced in the fuel to enter the reactor coolant. This source produces significantly more activity in the coolant than the tramp uranium does. Because the fission product activity in the coolant is much higher when there is a defect in the cladding, an increase in fission product activity can be one of the first indications of a fuel cladding defect. For a large fuel cladding defect, the change in activity will be rapid. However, the change in activity for a very small cladding defect may be so gradual as to not even be noticeable.

4.9 Detection of Fuel Cladding Failures

Detection of fuel cladding failures is an important part of plant operations. It is important to know if any fuel assemblies must be removed during a forthcoming refueling outage, and it is essential to make sure that the radioactivity limits for reactor coolant listed in the plant technical specifications are not exceeded.

Several techniques can be used to detect the presence of fuel cladding defects. One of the most common methods is gross activity analysis. A reactor water sample is taken daily or several times during a week, and its activity measured. The measurement is then plotted in terms of activity per milliliter of reactor water. The gross activity is the total activity of the sample. No attempt is made to identify any of the radionuclides. When the readings are plotted on graph paper, it is possible to follow any trend that may occur. If there is a small fuel cladding failure, such as a pinhole, it may not be detectable in terms of overall activity, but a large failure should show up immediately as a change in the slope of the plotted curve.

If a fuel failure is suspected on the basis of the gross activity analysis, another more precise analysis should be used. An analysis of gross iodine activity is more precise than an analysis of the overall activity. Iodine separation is one of the easier radiochemical separations, and iodine is one of the larger contributors to fission product activity. For this type of analysis, reactor water samples are taken and analyzed regularly, as was done for the gross activity analysis. The iodine is separated chemically, and the iodine activity is plotted on graph paper. The gross iodine activity is plotted with no attempt to determine which iodine radionuclides are present. If there is a sharp increase in the slope of the curve, it is reasonable to suspect a fuel failure.

The next step is an analysis of the iodine ratio. This analysis uses the same chemical separation of iodine that was made for the measurement of gross iodine activity. In this instance, however, an analysis is made for the activity of I-131 and I-133. The analysis is actually made in one of two ways:

1. A gamma spectrometer analysis can separate the peaks from the two nuclides and determine the amount of each that is present.

2. A ratio of I-131 to I-133 is determined by counting the sample after the I-133, which has the shorter half-life, has had a chance to decay.

In either case, if the I-133 activity increases significantly, it is likely that some new iodine has been introduced into the coolant as the result of a fuel failure.

Changes of activity in the coolant can be detected by radiation monitors in the off-gas line monitor for a BWR or the letdown cooling line monitor for a PWR. These gross activity monitors provide the first indication of a serious fuel cladding failure.

If fuel cladding failures are adding enough activity to the reactor coolant to affect plant operations, the failed fuel is usually removed during the next refueling outage. The problem is to determine which of the many fuel assemblies in the core are the failed ones. The first step in this determination is made while the reactor is operating at reduced power. It is called flux tilting, and it involves changing the relative positions of various control rods to increase the flux in one area of the core while reducing it in another area. The increased flux will cause any fuel with cladding failures to release more fission products into the coolant. The flux is systematically increased in different portions of the core, and either the off-gas activity (BWR) or the coolant fission product activity (PWR) is determined after each increase. An increase in activity indicates the presence of one or more failed fuel assemblies.

After the portions of the core that contain failed fuel assemblies have been identified, it is necessary to determine the exact fuel assemblies that have cladding failures. Individual assemblies are tested, generally by a technique known as sipping, after the reactor has been shut down and the vessel head has been removed. The sipping operation may be wet sipping, dry sipping, or wet-dry sipping.

In wet sipping, the fuel assembly to be tested is removed from the reactor core and placed in a can under water. The can is sealed, and the assembly is stored for a period of minutes or hours, depending upon the expected severity of the fuel failure. This allows the fission products to collect in the small space of the can where detection can be made more easily. At the end of the "soaking" period, a sample of water is taken (sipped) from the can and analyzed in the lab. That analysis usually includes the I-131 to I-133 ratio, but it may be just a gross activity analysis and/or a gross iodine analysis.

Dry sipping is similar to wet sipping, except that the water is pumped out of the can after the fuel assembly has been put into it. The assembly is allowed to heat up under controlled and measured conditions for a few minutes, and then water is allowed to re-enter the can from the bottom. The water displaces the gas up the sample tube where it can be sipped. The presence of fission gases (xenons and kryptons) indicates cladding failures.

Wet sipping will indicate the presence of large failures, while dry sipping generally detects even small failures. Wet-dry sipping is a combination of these two methods. The fuel assembly is placed in a can, and the water level is lowered until it is just above the assembly. The air in the area above the water is then pumped out past an on-line detector, which can detect a severe cladding failure by the presence of fission gases.

After the air has been pumped out, nitrogen gas is pumped in through the bottom of the can. The gas moves up past the fuel assembly and past the on-line detector and is then returned to the bottom of the can. This recirculation is continued for approximately 15 minutes while the radioactivity level is monitored. A steady increase in the radioactivity level indicates a fuel failure.

4.10 Ion Exchangers and Demineralizers

Ion exchangers and/or demineralizers are used in many power plant systems to improve the quality of the process water. Ion exchangers and demineralizers both act as chemical and physical filters to remove both soluble and insoluble impurities that might enter the process water through corrosion, erosion, or injection from other systems. Some systems may divert only a small part of the total system flow for cleanup, while other systems send full system flow through the ion exchangers or demineralizers. One example of partial flow cleanup is the letdown flow to the CVCS demineralizers in the PWR plant. An example of full system flow cleanup is the condensate system in most PWR and BWR facilities.

Ion exchange is basically the removal of undesirable ions in the process water using special resins. The special resins are complex polymers made from polystyrene and divinyl benzene. The polystyrene forms linear chains while the divinyl benzene acts as a cross-linking agent that can be used to control the physical properties of the resin. Resins with high degrees of crosslinking are desirable because they swell less when subjected to process water flow. Figure 4-9 shows the basic resin structure. Recent technology allows resin manufacturers to increase the percent of crosslinking without making the resin too brittle. These new resins are called macroporous or macroreticular. They have a greater affinity for large molecular weight ions because of their large pore structure.

In all resins, the ion exchange groups are attached to the aromatic rings in the polymer chains. A shorthand representation of common resins used in nuclear plants is shown in Figure 4-10. For cation resins, the exchange sites are negatively charged radicals of sulfonic salts that are initially "charged" or saturated with H^+ ions or other desirable cations like Li^+ (lithium). In the ion exchange process, the H^+ ions are exchanged for undesirable positive ions that have more affinity for the exchange sites than the H^+ ions do. For anion resins, the exchange sites are positively charged radicals of quarternary ammonium salts that are initially "charged" with OH^- ions. In the exchange process the OH^- ions are exchanged for undesirable negative ions that have more affinity for the ion exchange sites than the OH^- ions do. If a solution with ionic impurities is allowed to flow through a mixed cation and anion resin bed, the undesirable positive and negative ions in the solution will be removed by the ion exchange process. The effluent solution flowing from a mixed resin bed containing the resins shown in Figure 4-10 would contain H^+ and OH^- ions in place of the undesirable cations and anions.

Ion exchangers and demineralizers both use many small beads of porous polymer resin to accomplish the ion exchange process. The exchange sites are initially charged with desirable ions, such as H^+ and OH^- ions by flushing the resin with very strong solutions of these ions (acids and bases). When process water containing dissolved ionic impurities from corrosion or makeup water is subsequently flowed through the fully charged resin beads, the exchange sites exchange (release) a desirable ion for each undesirable ion encountered. The ion exchange process is not perfect; a few undesirable ions get through, but the exiting process water has a much lower concentration of undesirable ionic impurities than the entering water. In addition, the closely packed resin beads act as a physical filter for insoluble impurities (particulates) in the process water.

Eventually the resin beads become "exhausted" when all the exchange sites become filled with undesirable ions when the resin contains too much insoluble material. When this happens, increasing amounts of undesirable ions or insoluble impurities begin to get through the resin. At this point the "spent" resin is normally replaced with freshly charged resin. Many nuclear plants have sophisticated systems for removing the insoluble particles from spent resin, and some plants have systems for regenerating the ion exchange capabilities of the resin. However, most plants simply purchase new resin or hire private contractors to process the spent resin.

<u>Demineralizers</u> are a special form of ion exchanger. Demineralizer resins are always charged with H^+ and OH^- ions, and exchange the H^+ and OH^- ions for undesirable ionic impurities in the process flow. The H^+ and OH^- ions quickly combine in the exiting process flow to form pure water, H_2O, per the following reaction:

$$H^+ + OH^- \rightarrow H_2O.$$

Since the dissolved mineral ions have been removed, and the exiting flow is demineralized water, this type of ion exchanger is called a demineralizer. The ion exchangers used in condensate systems are normally demineralizers.

Other systems, such as the CVCS system in a PWR plant, often use ion exchangers that exchange a light metallic ion, such as lithium or barium, for other metallic impurities. The exiting process flow from these ion exchangers is not demineralized water, but rather is a slightly basic solution with Li^+ or Ba^{++} and OH^- ions. This slightly basic effluent solution improves the corrosion resistance of the reactor coolant piping. Ion exchangers that exchange something other than H^+ and OH^- ions to replace the dissolved mineral ions are referred to simply as <u>ion exchangers</u>.

An important principle of ion exchange is that resins exhibit a selective affinity for ions in solution. The relative affinity of resins for various cations and anions is shown in Table 4-6. The strongly held ions are at the top of each column, and the weakly held ions are at the bottom. As can be seen from the table, the greater the electrical charge on the ion, the stronger the affinity of the resin is for that ion. This characteristic of a hierarchy of affinity shown by resins for ionic impurities is known as <u>ion affinity</u>. The ion affinity listing shows why the H^+ and OH^- ions are normally used to charge fresh resins. The H^+ and OH^- ions are low on the ion affinity lists, meaning that they will readily exchange with (and remove) almost all of the undesirable ions, which are higher on the ion affinity lists.

The fluoride ion is low on the affinity listing and "leaks" through the ion exchanger resins more readily than other anions. Chloride ions will exchange with hydroxide ions, but chloride ions are not held as strongly as some of the other anions. Thus, if strict chloride control is required, care must be used that the resin is not depleted to the point where other anions begin to displace the chloride ions. Also note that cleanup of radioactive coolant water is facilitated by the fact that the iodine anion, containing the fission product I-131, is easily removed by resins due to its high affinity.

4.10.1 Deep Bed Demineralizers

Two basic types of ion exchanger systems are available. The first is the deep bed system which uses a tank partially filled with bead-type ion exchan_e resins. The second type is the powdered resin filter-demineralizer, which uses pulverized resins precoated onto nylon fibers or cellulose fillers surrounding stainless steel filter septa or tubes.

Deep bed condensate demineralizer systems are used on all saltwater cooled BWR units and on all PWR units. In these plants the added ion exchange capacity is necessary for protection against condenser cooling water in-leakage. Resins are loaded as mixed resins into spherical or cylindrical tanks (150 to 200 ft^3 resin per tank). A typical deep bed demineralizer is shown in Figure 4-11.

Two factors normally limit the length of the operating cycle of a deep bed demineralizer: exhaustion of the ion exchange capacity and reduced flow because of increased pressure drop resulting from crud or particulate buildup in the resin bed. In extreme cases the particulates begin to leak through the resin bed.

In the absence of condenser leakage, the pressure drop normally becomes the limiting factor. Bed performance can be optimized by a combination of ultrasonic cleaning and chemical regeneration. Ultrasonic cleaning is a mechanical cleaning process that removes the suspended particles or crud that has been collected in the resin bed. Ultrasonic cleaning is used when the pressure drop across the bed is excessive, but the ion exchange capacity is adequate.

When the ion exchange capacity of the resin bed is depleted, a more involved chemical regeneration process can be conducted. In this process, the cation resin beads are subjected to a strong acid solution; the anion beads, to a strong basic solution. The H^+ and OH^- ions replace the impurity ions at the reactive sites, and the ion exchange capacity of the resin is restored. However, if the resin was used in a radioactive coolant stream, the spent regenerant solutions are difficult to process and discard. Therefore, most plants normally opt for the simpler solution of replacing the depleted ion exchange resin with new resin.

The advantage of a deep bed demineralizer over a powdered resin filter-demineralizer is the relatively large ionic capacity of the deep bed. This capacity provides an adequate ion exchange margin to allow an orderly plant shutdown following a significant condenser leak with its attendant ingress of ionic impurities.

4.10.2 Powdered Resin Filter Demineralizers

The type of condensate demineralizer system normally used in BWRs with freshwater cooling is the powdered resin filter demineralizer (see Figure 4-12).

The powdered resin system basically consists of ground-up, mixed bed resins that are precoated onto the filter elements, which consist of fibrous material wound or mechanically held onto a central filter tube. The quantity of resin used in such a system is small compared to the deep bed systems. Because of the smaller ion exchange capacity of powdered resin systems, they are not used for feedwater purification where salt water condenser cooling is employed. Powdered resin beds do not afford the ion exchange margin needed following the start of a salt water condenser tube leak. The powdered resin system does, however, provide suitable protection for small leaks in a fresh water cooled plant. Depleted or clogged elements in powdered-resin demineralizers are normally not regenerated or cleaned, but are barreled and discarded after use.

Because the fibrous material is a much better particulate filter than the loose deep bed resin, the efficiency of the powdered resin filter demineralizer for insoluble material removal is better than the corresponding deep bed efficiency. Powdered-resin systems in many cases remove more than 99% of the insoluble material. However, there are always thin resin layer areas that experience rapid ionic impurity breakthrough. As a result, effluent conductivities are often higher than those for deep bed systems.

For the deep bed system, only limited ionic breakthrough is expected until a good deal of the available capacity has been exhausted. For powdered resin, ionic breakthrough is approximately linear with the percent of resin exhaustion. This linear ionic breakthrough characteristic occurs because there are areas of very thin resin layers that rapidly become exhausted.

4.11 Basic Water Chemistry Requirements

Sections 4.1 and 4.2 described the measurement of pH and conductivity in nuclear plants. The differences between the uses of these measurements in BWR and PWR plants was discussed in section 4.2.

Nuclear plants measure other chemical parameters, and some of these measurements also differ between BWR and PWR plants. For instance, most PWR plants sample the reactor coolant for fluoride and chloride ions, and dissolved oxygen, all of which directly affect the plant piping susceptibility to stress corrosion cracking. PWR plants attempt to maintain the concentrations of these dissolved impurities at the minimum detectable levels. If the ion levels start to trend upward, the efficiency of the makeup water demineralizers is checked. If the dissolved oxygen level increases, the status of the hydrogen overpressure in the volume control tank is checked.

Fluoride ions and dissolved oxygen are not normally measured in BWR plants because these contaminants go off as a gas with the steam, and subsequently get removed by the condenser air removal equipment. Therefore, BWR plants limit their required sampling to chlorides and the conductivity measurements described in Section 4.2. If either the chloride levels or the conductivity results start to increase significantly, the efficiency of the feedwater demineralizers is checked.

Both PWR and BWR plants periodically sample for trace elements such as silicon, calcium, and magnesium. The frequency of these periodic samples is increased if the plant conductivity measurements show an increase in total dissolved ions.

When the level of dissolved ions does start to increase, the frequent cause of the increase is exhaustion of the plant ion exchangers. The ion exchangers remove undesirable ions from the plant waters; if the efficiency of ion exchangers decreases, the number of ions passing unaffected through the ion exchangers begins to increase. Both BWR and PWR plants run a periodic decontamination factor check for the on-line ion exchangers. The decontamination factor is defined as the concentration of an impurity entering an ion exchanger divided by the concentration of the same impurity exiting the ion exchangers. This relationship is shown in Equation 4-5:

$$\text{Decontamination Factor} = \frac{\text{Impurity concentration entering ion exchanger}}{\text{Impurity concentration exiting ion exchanger}} \quad (4\text{-}5)$$

The impurity concentrations being measured can be either conductivity (total dissolved solids), long-lived radioactivity (crud), or specific impurities.

Many plants use a decontamination factor of 25 (96% efficiency) as a cutoff for determining if the resin is exhausted. If the decontamination factor decreases below 25, the ion exchanger is replaced and/or regenerated.

Chapter 4 Definitions

ACID	-	A chemical compound that produces hydrogen ions (H^+) when dissolved in water.
BASE	-	A chemical compound that produces hydroxide ions (OH^-) when dissolved in water.
pH	-	The inverse logarithmic measure of the hydrogen ion concentration in a solution. Specifically, pH is the negative logarithm of the molar concentration of the hydrogen ion in a solution.
CONDUCTIVITY	-	The conductance of a solution measured at 25°C between two electrodes that are each 1 cm^2 in area and spaced 1 cm apart.
RADIOLYTIC DISSOCIATION OF WATER	-	The breaking of the hydrogen-oxygen bonds in a water molecule that has been struck by a neutron.
RADIOLYTIC RECOMBINATION OF WATER	-	The reconstitution of broken hydrogen-oxygen bonds to form water in a strong gamma flux.
CRUD TRAP	-	A low flow velocity area where crud carried by a coolant stream can settle and accumulate.
CRUD BURST	-	The sudden return of many crud particles from various piping surfaces to the coolant stream.
DECONTAMINATION FACTOR	-	The concentration of an impurity entering an ion exchanger divided by the concentration of the same impurity exiting the ion exchanger.

Table 4-1. pH and Ion Concentrations

	pH	H+ Concentration (moles/liter)	OH- Concentration (moles/liter)
	0	10^{0}	10^{-14}
Increasingly	1	10^{-1}	10^{-13}
Acid	2	10^{-2}	10^{-12}
Solutions	3	10^{-3}	10^{-11}
↑	4	10^{-4}	10^{-10}
	5	10^{-5}	10^{-9}
	6	10^{-6}	10^{-8}
Neutral	7	10^{-7}	10^{-7}
	8	10^{-8}	10^{-6}
	9	10^{-9}	10^{-5}
↓	10	10^{-10}	10^{-4}
Increasingly	11	10^{-11}	10^{-3}
Basic (Alkaline)	12	10^{-12}	10^{-2}
Solutions	13	10^{-13}	10^{-1}
	14	10^{-14}	10^{0}

Table 4-2. Activated Corrosion Products

Nuclide	Half-Life	Formation Mechanism
Cr-51	27.8 days	$Cr^{50}(n, \gamma)Cr^{51}$
Mn-54	312 days	$Fe^{54}(n, p)Mn^{54}$
Mn-56	2.58 hours	$Fe^{56}(n, p)Mn^{56}$ and $Mn^{55}(n, \gamma)Mn^{56}$
Fe-59	45 hours	$Fe^{58}(n, \gamma)Fe^{59}$ and $Co^{59}(n, p)Fe^{59}$
Co-58	71 days	$Ni^{58}(n, p)Co^{58}$
Co-60	5.24 years	$Co^{59}(n, \gamma)Co^{60}$ and $Ni^{60}(n, p)Co^{60}$
Cu-64	12.9 hours	$Cu^{63}(n, \gamma)Cu^{64}$
Zn-65	243 days	$Zn^{64}(n, \gamma)Zn^{65}$
W-187	24.0 hours	$W^{186}(n,\gamma)W^{187}$

Table 4-3. Radioiodines

Nuclide	Half-Life	Fission Yield (%)	Fission Gas Daughter
I-131	8.05 days	2.835%	
I-132	2.28 hours	4.208%	
I-133	20.8 hours	6.765%	Xe-133
I-134	52.6 minutes	7.612%	
I-135	6.58 hours	6.406%	Xe-135m/Xe-135

m = metastable variant

Table 4-4. Fission Gases

Nuclide	Half-Life	Fission Yield (%)
Xe-138	14.2 minutes	6.235
Kr-87	76 minutes	2.367
Kr-88	2.79 hours	3.642
Kr-85m	4.4 hours	1.332
Xe-135	9.16 hours	6.723
Xe-133	5.27 days	6.776
Xe-135m	15.7 minutes	0.05
Kr-85	10.76 years	0.27

m = metastable variant

Table 4-5. Soluble Metal Ions

Nuclide	Half-Life	Fission Yield (%)
Mo-99, Tc-99m	66.6, 6.0 hours	6.136, 5.399
Zr-95, Nb-95	65.5, 35.1 days	6.503, 6.505
Ba-140, La-140	12.8 days, 40.2 hours	6.300, 6.322
Cs-137	30.2 years	6.228
Sr-89	50.8 days	4.814
Sr-90	28.9 years	5.935
Ce-141	32.5 years	5.867

m = metastable variant

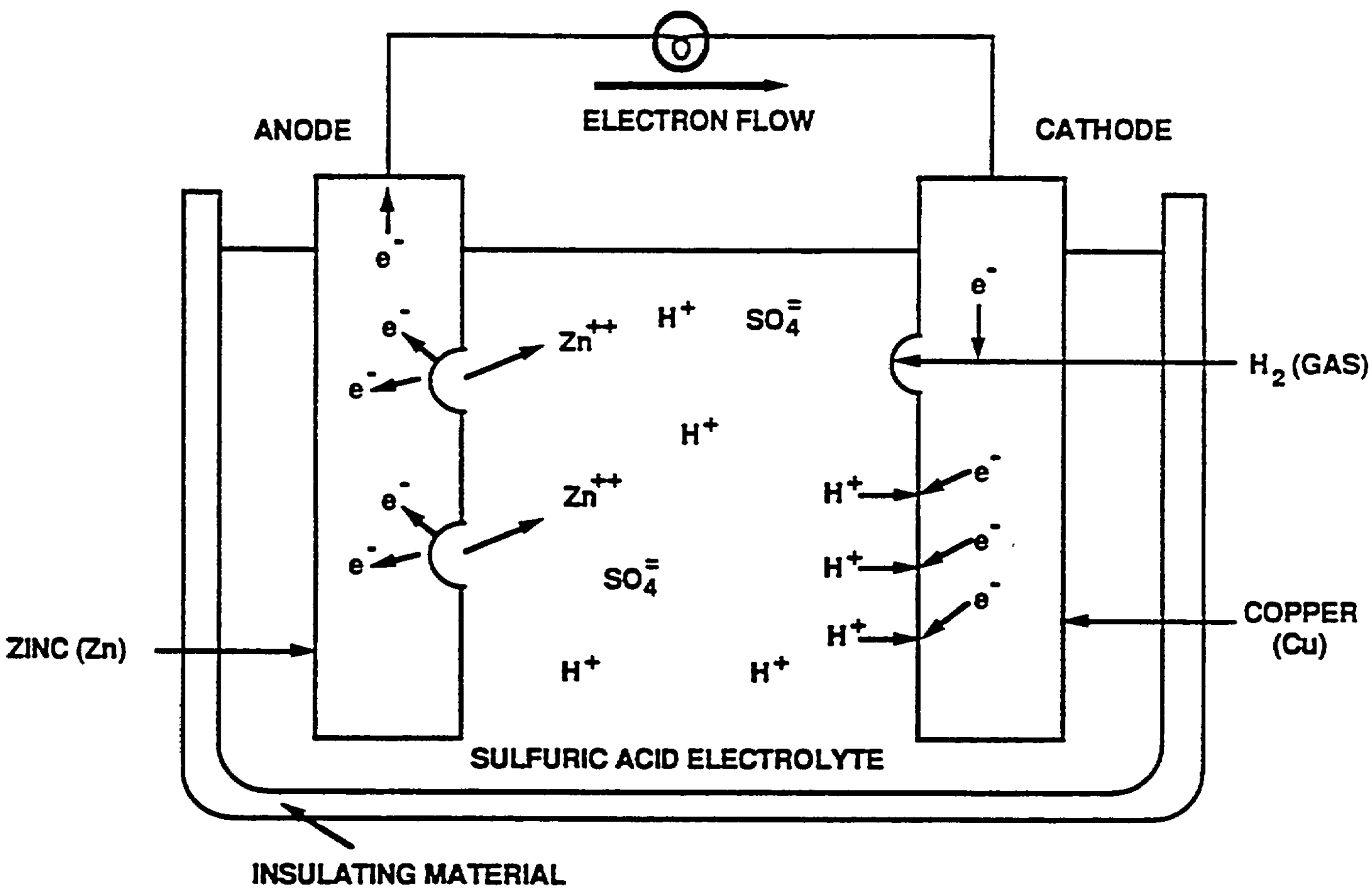


Figure 4-1. Voltaic Cell Operation

Table 4-6. Resin Affinity

Cation Resin	Anion Resin
Fe^{+++}	I^-
Ba^{++}	NO_3^-
Sr^{++}	Br^-
Ca^{++}	HSO_4^-
Cu^{++}	Cl^-
Zn^{++}	HCO_3^-
Ni^{++}	IO_3^-
Co^{++}	SiO_2^-
Fe^{++}	OH^-
Mg^{++}	F^-
Ag^+	
Ti^+	
Cu^+	
Cs^+	
Rb^+	
NH_4^+	
K^+	
Na^+	
H^+	
Li^+	

NOTE: The degree of resin affinity for cations or anions decreases from top to bottom

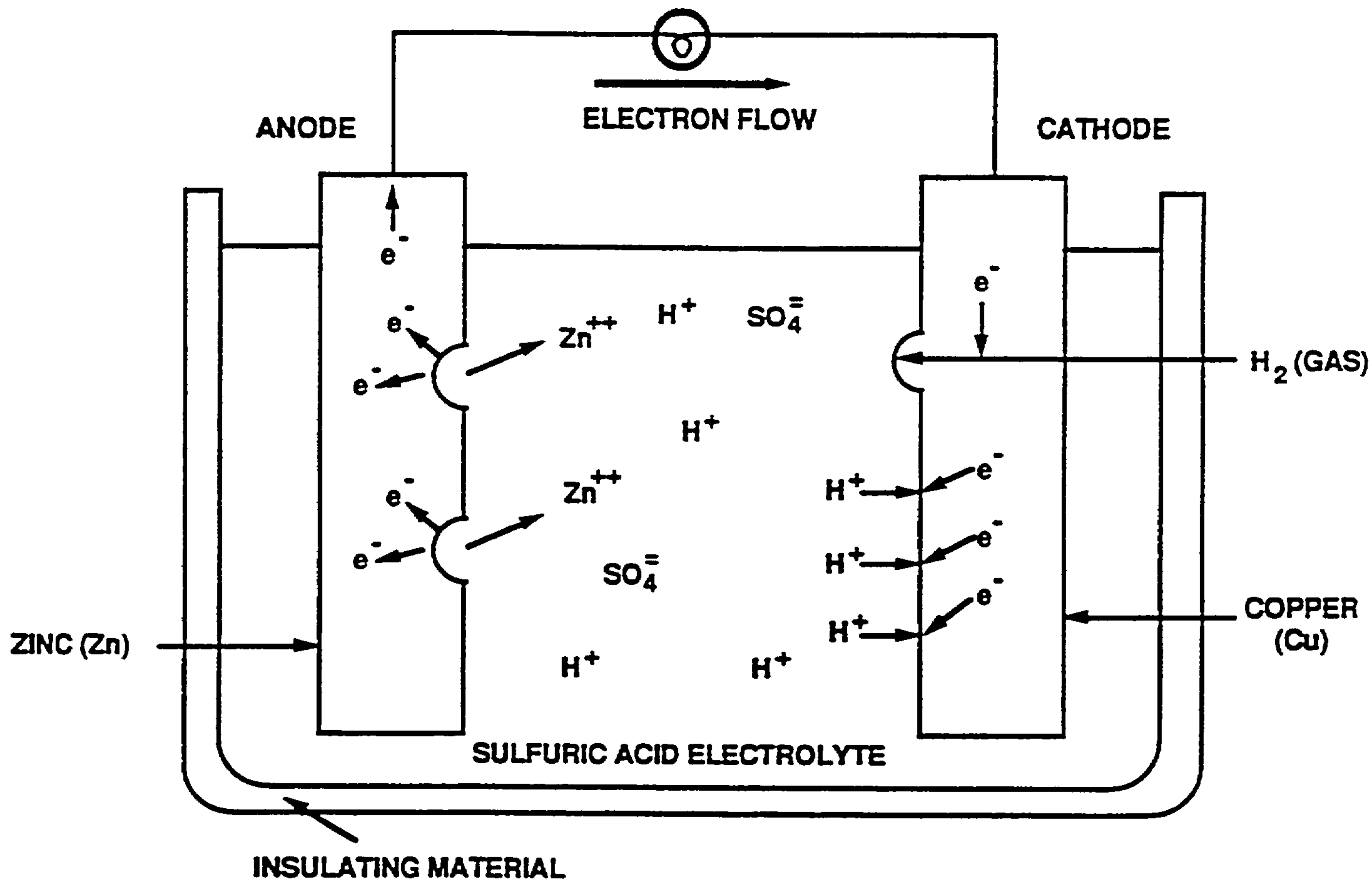
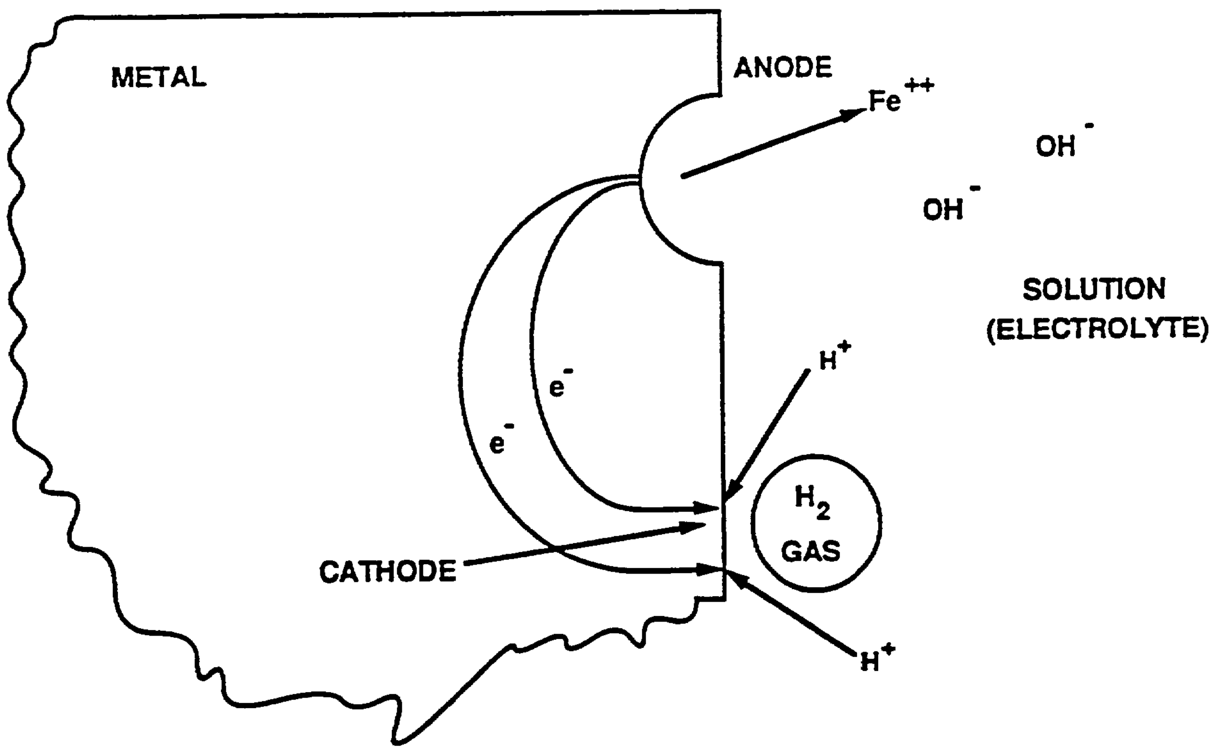


Figure 4-1. Voltaic Cell Operation



	DISSOLVED OXYGEN PRESENT	NO DISSOLVED OXYGEN PRESENT
ANODE REACTION	$2Fe \rightarrow 2Fe^{++} + 4e^-$	$Fe \rightarrow Fe^{++} + 2e^-$
CATHODE REACTION	$O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$	$2H^+ + 2e^- \rightarrow H_2$
INTERIM REACTION	$Fe^{++} + 2OH^- \rightarrow Fe(OH)_2$	$Fe^{++} + 2OH^- \rightarrow Fe(OH)_2$
FINAL REACTION	$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 + 4H_2O$	$3Fe(OH)_2 \rightarrow Fe_3O_4 + H_2 + 2H_2O$
COMBINED REACTION	$4Fe + 3O_2 \rightarrow 2Fe_2O_3$ (rust)	$3Fe + 4H_2O \rightarrow 4H_2 + Fe_3O_4$ (magnetite)

Figure 4-2. Corrosion of Iron

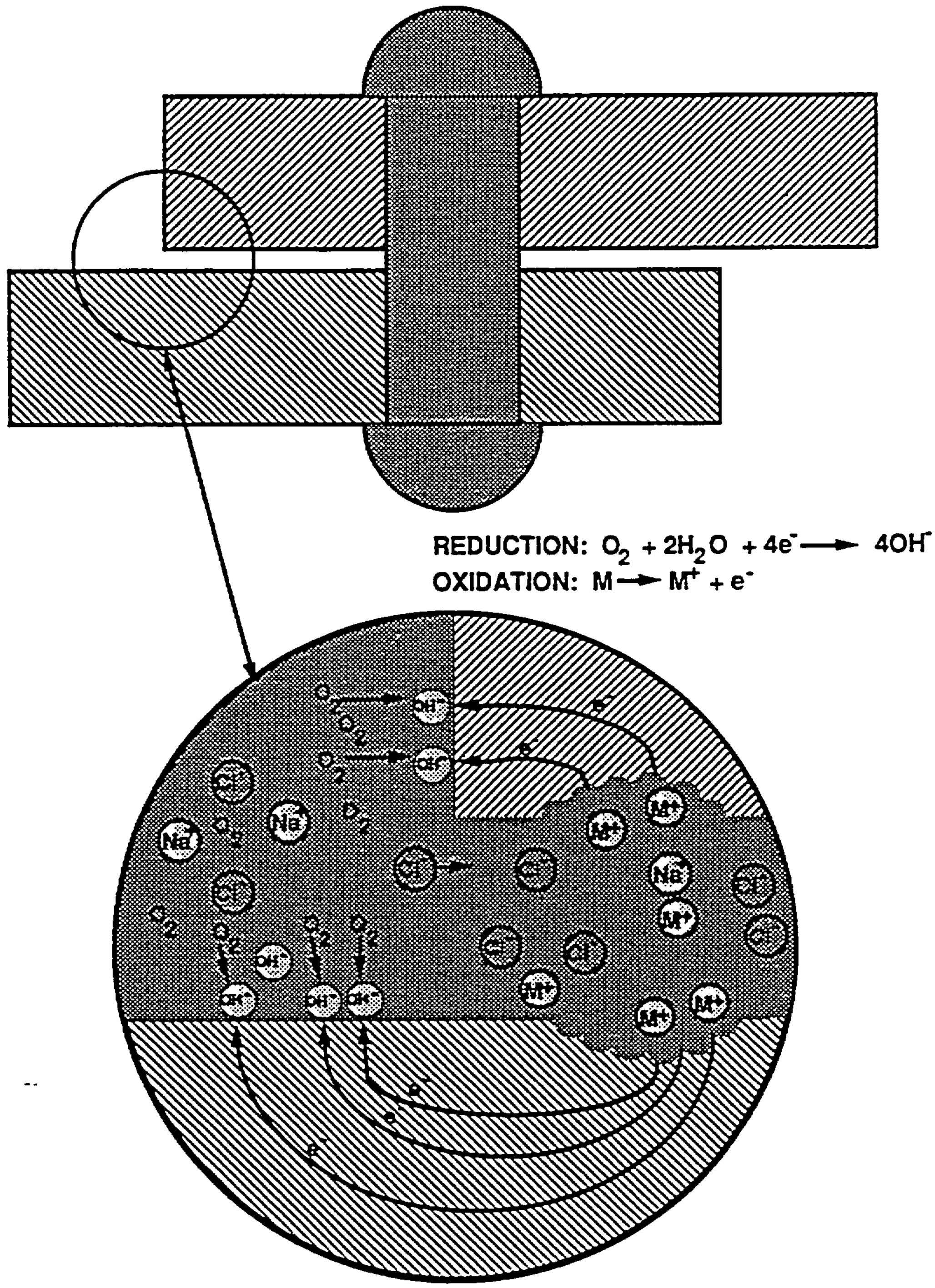


Figure 4-3. Crevice Corrosion

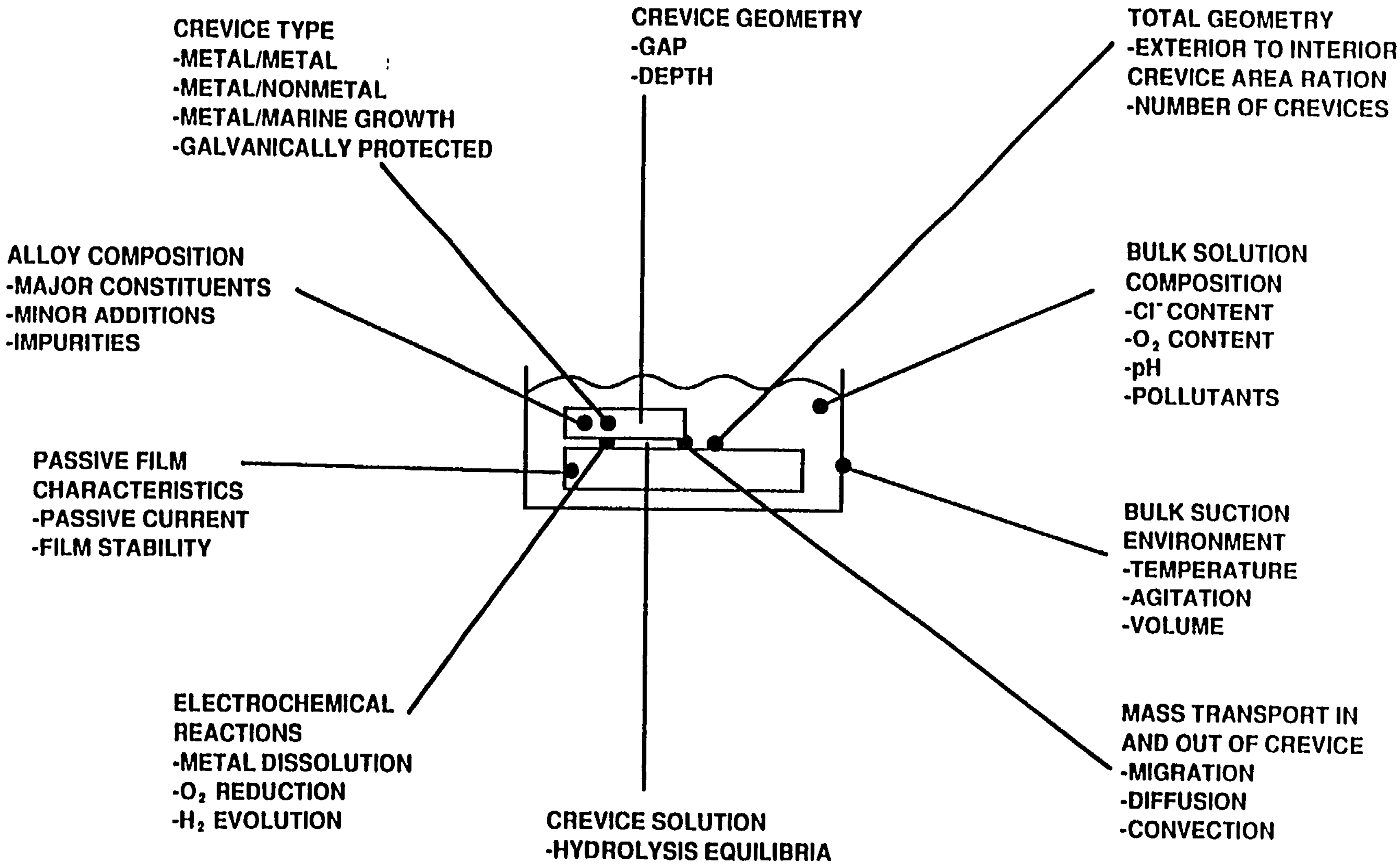


Figure 4-4. Factors Affecting Crevice Corrosion

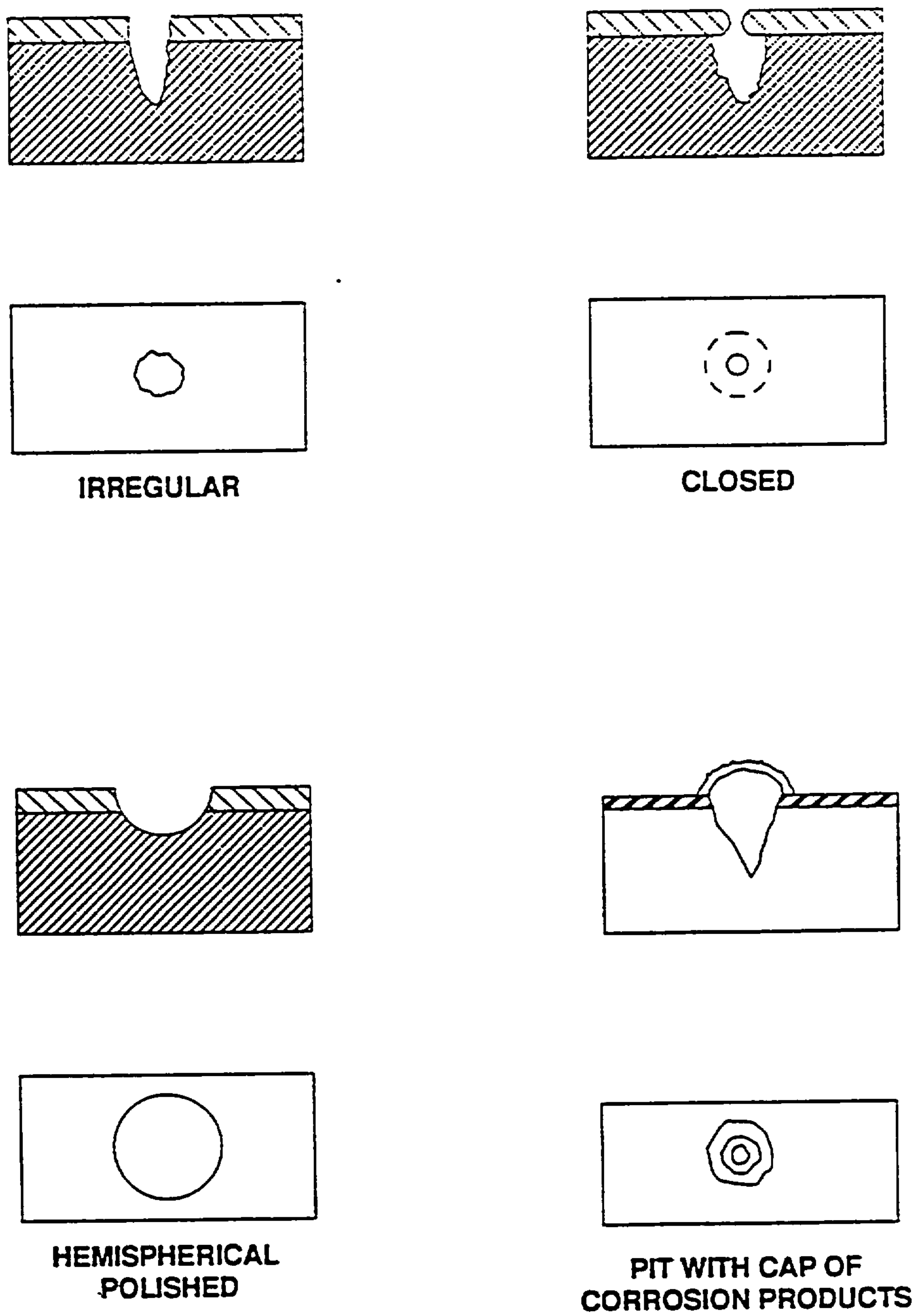


Figure 4-5. Pitting Corrosion

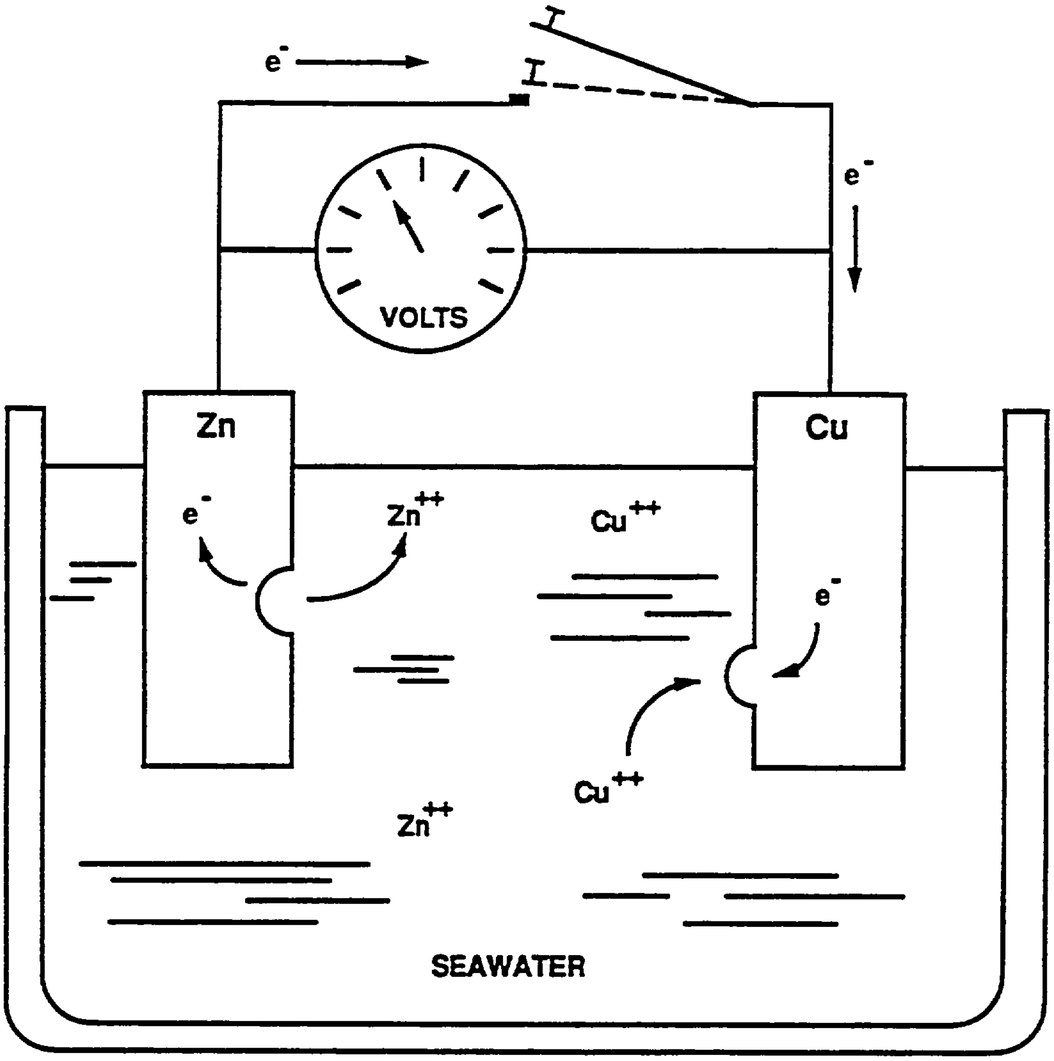


Figure 4-6. Cu-Zn Galvanic Cell

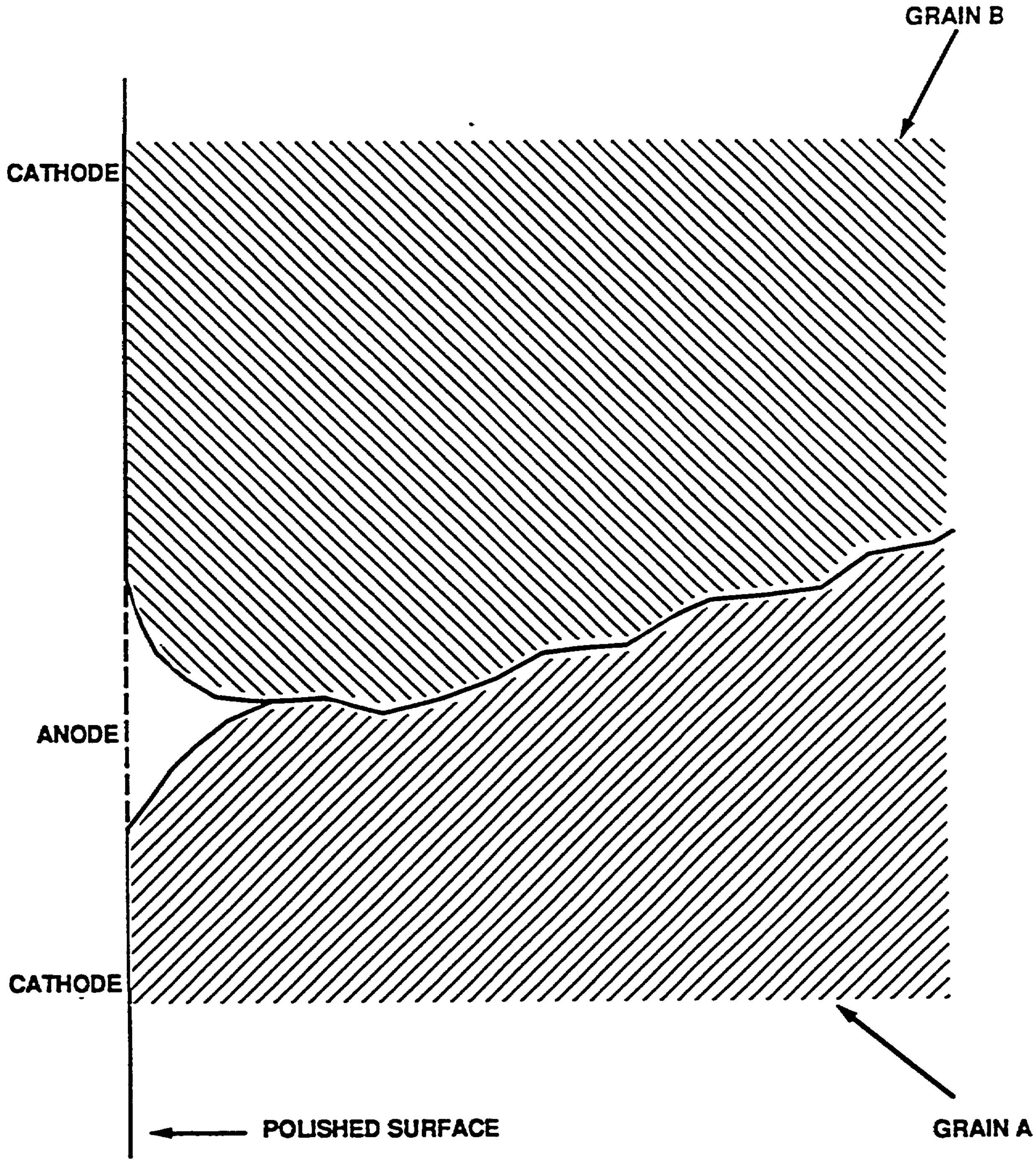


Figure 4-7. Intergranular Corrosion

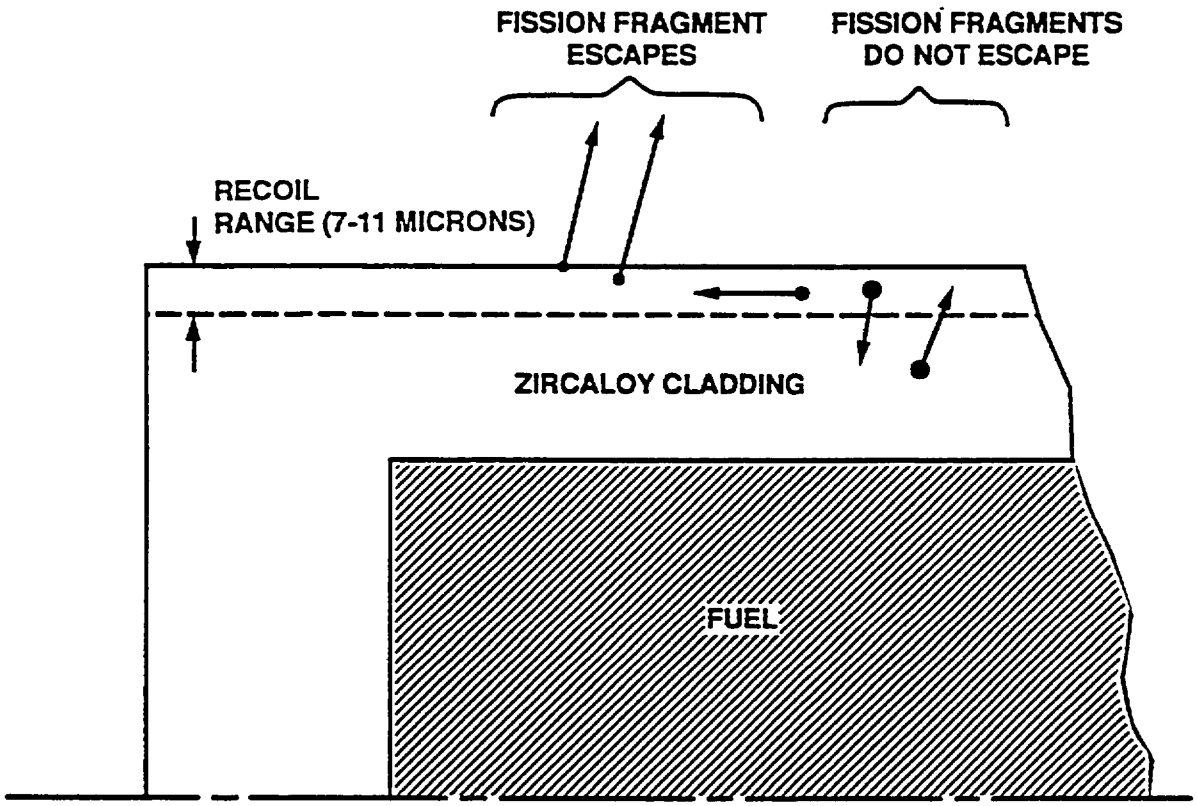
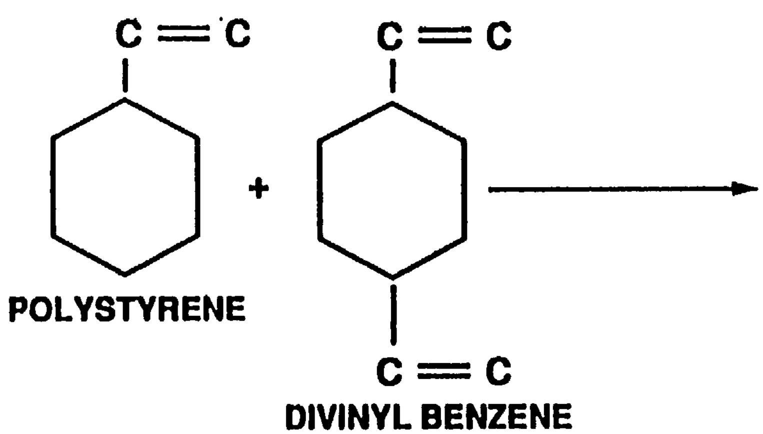
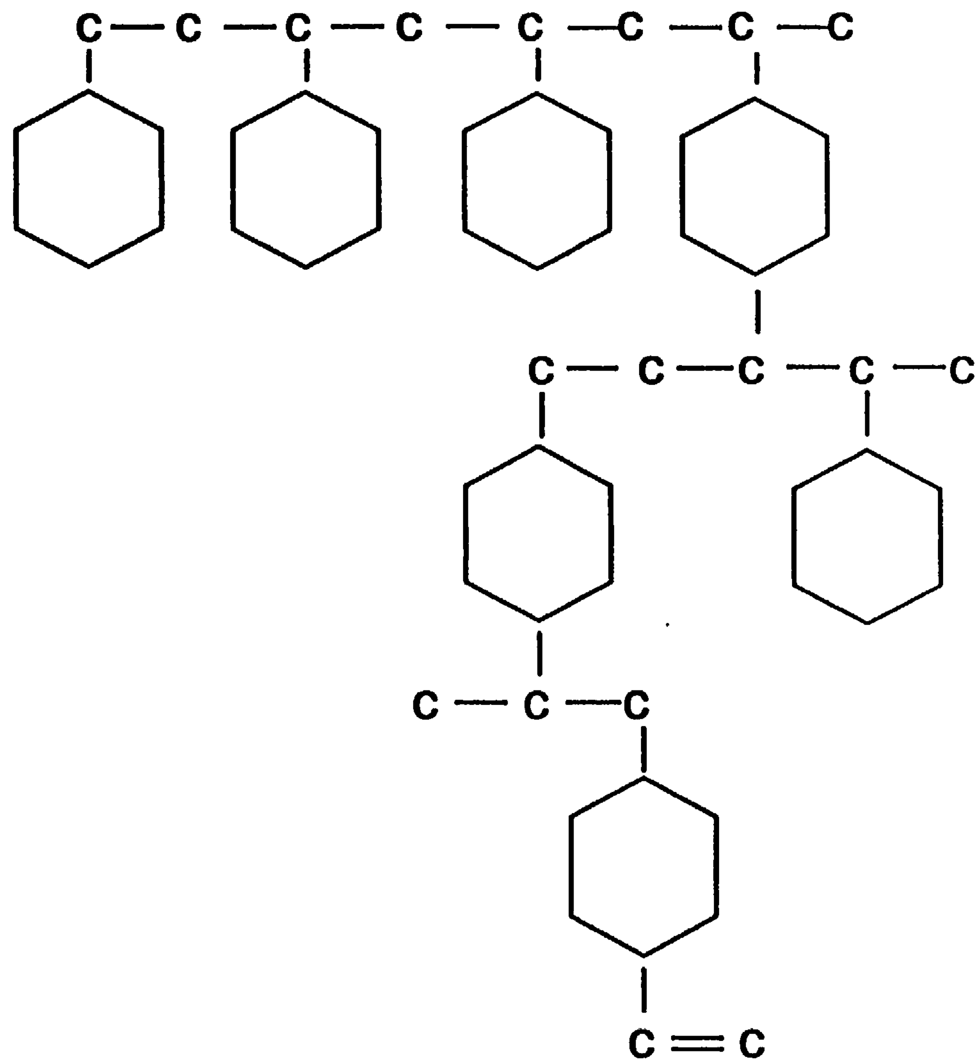


Figure 4-8. Recoil Range

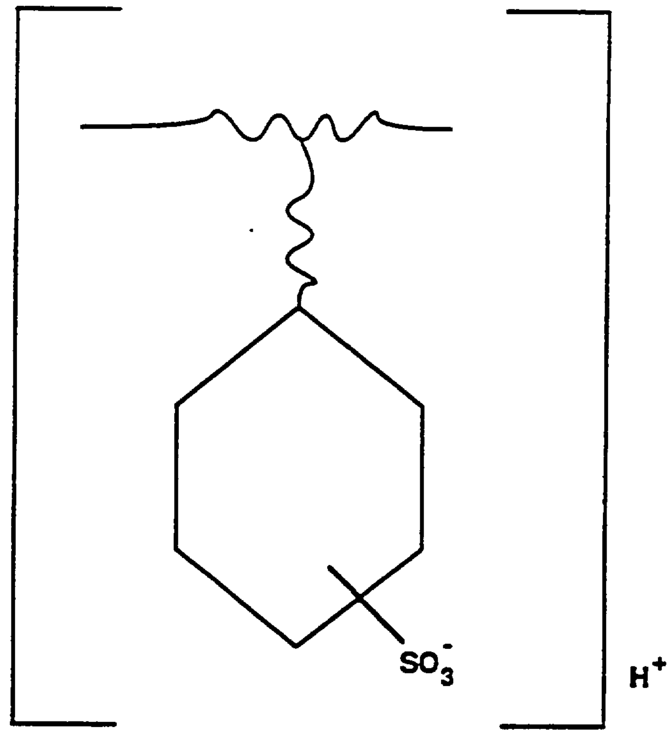




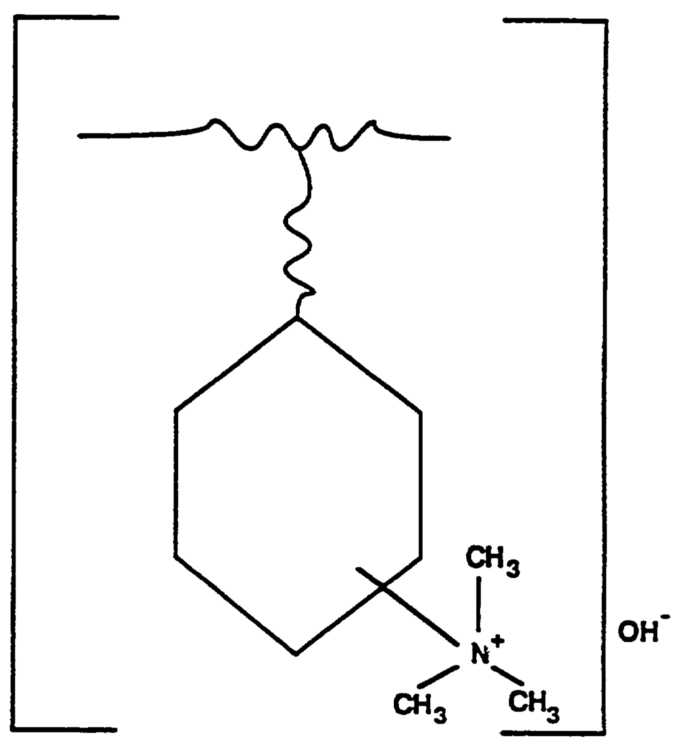
POLYSTYRENE: LINEAR STYRENE CHAINS

DIVINYL BENZENE: CROSS-LINKING AGENT
(4% TO 10%)

Figure 4-9. Basic Resin Structure



CATION RESIN



ANION RESIN

Figure 4-10. Common Resin Representations

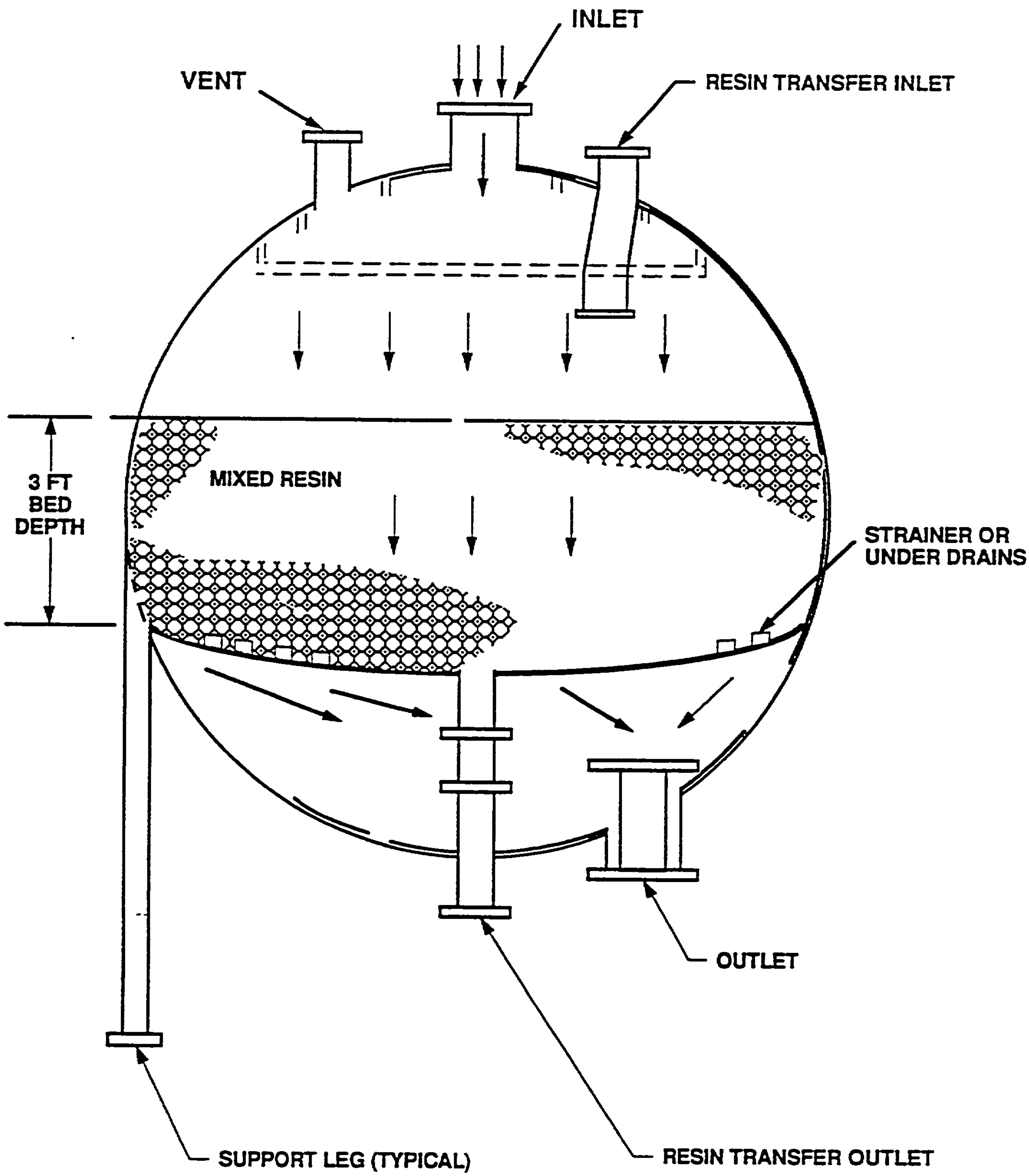


Figure 4-11. Deep Bed Demineralizer

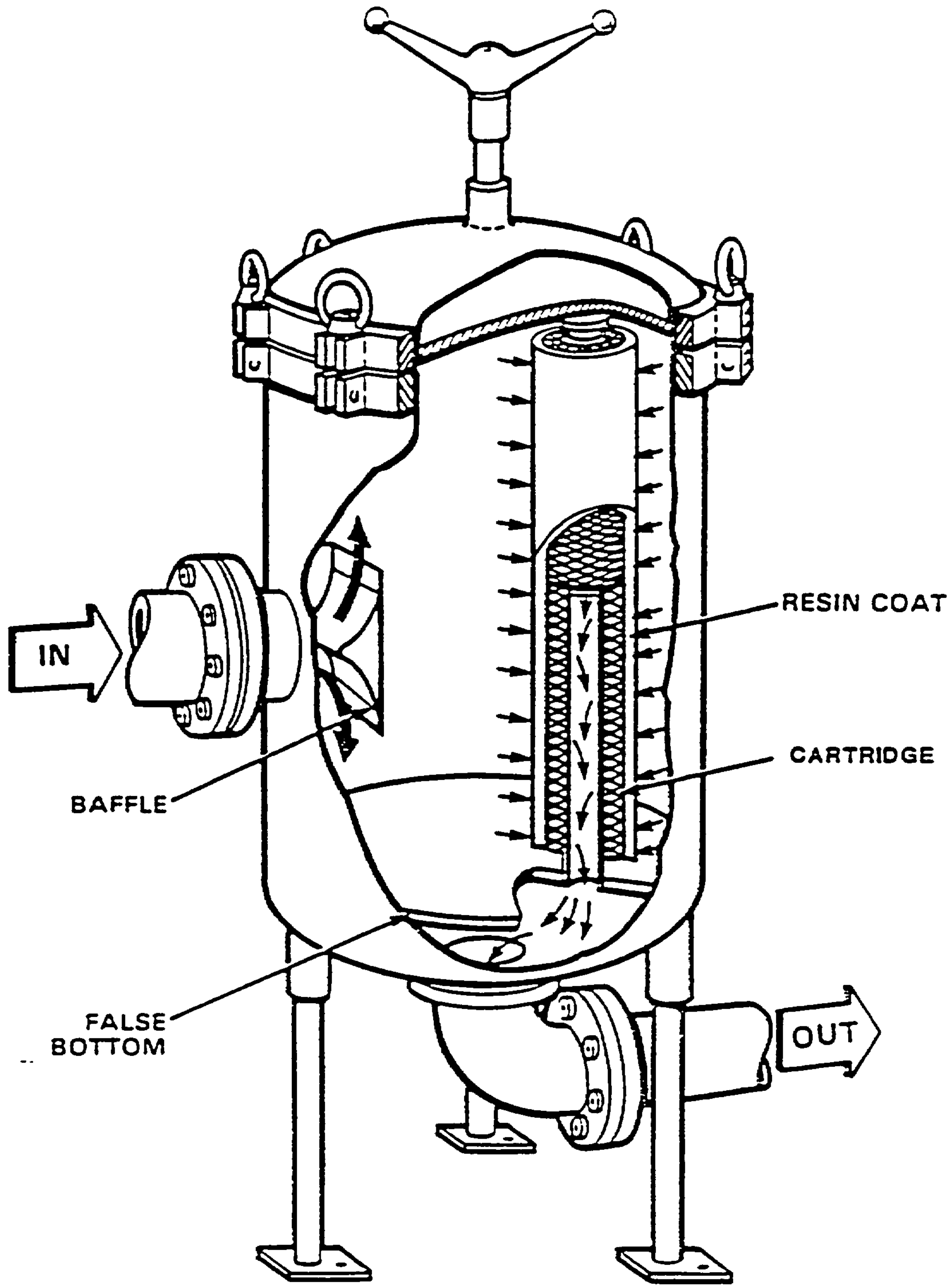


Figure 4-12. Typical Filter/Demineralizer Unit

5.0 PRINT READING

Learning Objectives

After studying this chapter, you should be able to:

1. Describe the characteristics of a "controlled" drawing and an "information only" drawing.

2. For a piping and instrumentation drawing (P&ID):
   a. Trace a flow path from the source through to the delivery point.
   b. Determine whether a specific valve is normally open or normally closed.
   c. Determine the type of actuator and fail position of a specific valve.
   d. Determine the meaning of the notations used on a specific piping run.

3. For elementary electrical drawings (control wiring diagrams):
   a. Determine whether specific relay contacts are shown open or closed, and what actuates them to the other condition.
   b. Trace a start/stop signal through to the closing/trip coil.

4. Use one-line electrical distribution system drawings to determine system and component voltages.

5. Given a logic diagram for an actuation function and the status of the accompanying inputs, determine the output condition of the function.

6. Describe the characteristics of coincidence logic and selective coincidence logic.

5.1 Introduction

Nuclear plant personnel must be familiar with many different types of technical reference documents to perform assigned job functions. Mechanical and electrical schematics and drawings (often referred to as prints) are among the most important. New personnel must quickly learn to interpret piping and instrumentation drawings (P&IDs) and one-line electrical drawings.

Because each plant produces their drawings in a slightly different format, this chapter presents examples of drawings from several plants. Exposure to several different formats will allow students to understand other formats that they may encounter in the future.

5.2 Categories of Drawings

Drawings and schematics are often categorized by drawing purpose. Purposes include:

- To describe piping system connections, accomplished in piping and instrumentation drawings (P&IDs).

- To describe electrical control circuitry for breakers or motors, accomplished in control circuit wiring diagrams.

- To describe power supplies, loads and the electrical connections between them, accomplished in one-line electrical drawings.

- To describe the conditions required for automatic operation of system components, accomplished in logic diagrams.

- To describe the physical location of equipment components with respect to one another, accomplished in plan views, elevation drawings, and isometric drawings. Isometric drawings are used to show spatial arrangements of three-dimensional piping systems or components on a two-dimensional surface using 120° angles and same-scale (isometric) foreshortened lengths.

5.2.1 Drafting Organization

Several different organizations produce drawings for use at commercial nuclear power plants.

Examples include:

- Vendor - usually provided with vendor manuals for specific pieces of equipment, such as GE turbines.

- Plant architect/engineer - used for both construction and system modifications.

- Utility engineering department - normally takes responsibility for maintaining and modifying plant drawings after plant begins operating.

5.2.2 Status of Modifications

Drawings are also categorized by the status of changes and modifications that have been made to a system. The following are common examples of the drawing categories used at a nuclear plant:

- As-designed drawings - reflect the original design for the system (often modified during construction due to unforeseen interferences).

- Baseline or As-Built drawings - reflect the current as-is conditions in the plant.

- Interim drawings - reflect proposed changes to a baseline drawing or modifications not yet installed.

- Construction drawings - interim drawings used to modify the plant.

- As-Installed drawings - reflect a complete modification that has been installed in the plant.

It is important to note that in some cases both as-designed and as-built drawings (and sometimes even testing drawings) can exist simultaneously for the same system. Additionally, current system component lineups may have been altered from that shown on the plant drawings to perform surveillances, maintenance, testing, or temporary alterations. The drawing user must ensure that the P&ID selected is proper for the intended use and that any short-term alterations to the system are known.

5.2.3 Controlled vs. Information Only

Copies of official plant drawings are typically maintained in files at several locations throughout the plant. Each of these locations will have either "controlled" or "information only" copies, depending on the normal usage at that location.

Controlled copies are maintained up-to-date by authorities designated in the standard operating procedures and can be found only in designated locations. These drawings are the most accurate and up-to-date drawings available, and all revisions and Engineering Change Notices (ECNs) have been entered on them. Only controlled drawings should be used for construction, maintenance, operations, or testing. Although each plant uses different identification methods, controlled drawings can always be easily identified. The most common method includes a specific color of paper and/or a large red "CONTROLLED" stamp on each drawing. A complete set of controlled drawing copies is normally maintained in or near the control room of every plant.

Drawing copies not identified as "controlled" are normally identified as "information only" copies. Information only copies are used for reference and training. They may be obtained by making a non-controlled copy of a drawing from one of the designated "controlled" locations. Also, some plants may provide operator trainees with information only copies of the most commonly used diagrams. Information only copies are frequently a different color from controlled drawings and are stamped "INFORMATION ONLY."

5.3 Print Reading Fundamentals

Drawings and schematics of all types (except training department sketches) are often referred to as prints. Every print will contain standard information required to identify the print, the equipment or systems shown on the print, and any cross-referencing with other prints. These functions are accomplished by print indexes, title blocks, numbering systems, and grids.

5.3.1 Indexes

Print indexes are usually organized by drawing purpose. There is one index for all P&ID drawings, another for all one-line electrical drawings, etc. Each index contains the print number and a brief description of the system(s) included in the print. Figure 5-1 is a copy of a partial print index.

Other indexes that are usually provided with prints include an equipment list, valve designation list, and instrument list. Equipment lists usually include the equipment noun name and number, print number and grid location, horsepower or kilowatt load, speed in rpm, pump ratings in gpm, or heat exchanger capacity in BTU/hr.

Valve designation lists usually include the valve identification number, print number and grid location, valve size, pressure rating, and valve type.

Instrument lists usually include the instrument identification number, brief description, P&ID drawing number, one-line electrical drawing number, logic diagram number, and the location or panel number of the instrument readout.

5.3.2 Title Block

All plant drawings or prints have a title block in the lower right hand corner. A very simple title block is shown in Figure 5-2. All title blocks should include:

- Originating organization or company name,
- Drawing title,
- Drawing number,
- Drawing revision number, and
- Approval notations.

Revision history blocks are often included with the title block to document all changes made to the drawing since it was originally produced.

5.3.3 Numbering Systems

Most plants have a unique numbering system for both their prints and the equipment shown in the prints. The following information is usually included in the print numbering system.

- Unit (for facilities with more than one unit),
- System (ie., reactor coolant, auxiliary steam), and
- Drawing purpose (P&ID, one-line electrical, logic diagrams).

Equipment numbering systems usually include the following information:

- System (ie. reactor coolant, auxiliary steam),
- Component type (ie. pump, valve, tank), and
- Component number - Unique numbers are given to each component in the system. For example, valves in a system will be numbered "1,2,3, ..." Numbers in the one thousand series may be assigned to smaller instrument (line) valves.

5.3.4 Grids

Most prints have a grid system labeled on the edges of the drawing (see Figure 5-2). Typically, the horizontal axis is numbered from right to left and the vertical axis is lettered from bottom to top. The grid system is used to locate individual components. The grid system also allows components and piping connections on other prints to be referenced with appropriate drawing numbers and grid locations.

5.3.5 Revisions

Drawing revisions are provided to keep the prints up-to-date with modifications made to the plant. The number of times a print has been revised (Revision Number) is located in or near the title block. A separate revision block is sometimes included near the title block. The revision block summarizes the changes made by each revision and include the effective dates and approval signatures. The part of the drawing affected by the revision may be identified by a small triangle containing the revision number, or areas that have been recently modified may be enclosed in a wavy "cloud" line. Some plants use red-line revisions on control room drawing copies to indicate modifications that have not yet been annotated on the formal drawing. Other plants use different identification methods, for these recent revisions, such as colored paper or green-line annotations.

5.4 Piping and Instrumentation Diagrams

P&IDs are used to describe piping systems throughout the plant. P&IDs are usually used to determine and/or verify one or more of the following:

- The function of a valve or other component known to exist in the plant;
- The identification number of a system component;
- Valve lineups necessary to establish a desired flowpath or isolate a specific component for maintenance;
- The cause of an undesirable flow restriction or isolate an undesirable leak;
- The function or purpose of part or all of a system and its components;
- The type and location of instrumentation; and
- Valve types and pipe sizes.

5.4.1 P&ID Symbols

P&IDs use symbols to represent components in a system and to show the physical relationships between components. P&IDs also show where instrumentation is provided for measuring and indicating variables and control processes.

To interpret the information provided on P&IDs, personnel must be familiar with the symbols used on the prints. The P&ID legend or symbol list includes the name and a brief description of each symbol. Usually P&ID legends from different plants are slightly different; however, many common symbols are consistent throughout the industry.

An example of a P&ID symbol list is included in Figure 5-2. Figures 5-3 and 5-4 provide enlarged views of portions of the symbol list shown in Figure 5-2.

P&IDs are typically drawn to show component lineups as they exist during normal at-power operation of the plant. Therefore, the valve symbols are shaded to indicate whether the valves are normally open or normally closed when the plant is operating at power.

5.4.2 P&ID Examples

The following sections discuss examples of different types of P&IDs.

5.4.2.1 Diesel Generator Air Start System

Before attempting to gather information from a P&ID drawing, the user should have a basic understanding of the system operation. This can be accomplished by referring to the simplified training department sketch of the system.

Figure 5-5 is a training department sketch of an emergency diesel generator air start system. This system provides low pressure air to two air motors that move the engine crankshaft until the combustion cycle takes over. This is accomplished by supplying air to an air relay valve through a solenoid operated valve and two valves that are open when the air motors are engaged with the crankshaft flywheel. When the air relay valve is supplied with air, the main air supply will reach the air motors and start the diesel.

Figure 5-6 is a portion of the P&ID for the diesel air start system. It is more detailed than the training department sketch and contains valve types, valve identification numbers, pressure switches and indicators, alarms, and relief valves.

The diesel air start system P&ID indicates that valves SA-153 (grid location D-6), SA-170 (B-6) and SA-190 (C-5) are normally closed gate valves. SA-165 (C-3) is a normally closed globe valve. SA-192 (D-3) is the solenoid valve referred to in the training drawing and SA-196 (C-3) is the air relay valve, both of which are normally closed.

One of the most important functions of a P&ID is to provide information on the location and function of all sensing and control elements used in the system. The legend on the bottom right of the print provides instrumentation details. For example, pressure switches 4 and 6 (PS-4 at C-4 and PS-6 at E-4) provide both local and remote alarms and computer inputs Y3360 and Y3361. The location of these alarms could be determined by referring to PA-3360 and PA-3361 in the instrument log list. Pressure indicators 6 and 7 (PI-6 and PI-7 at C-4 and E-4) provide local indication of starting air pressure. PS-3 and PS-5 (E-5 and B-5) provide control signals for compressor operation. Relief valves SA-154, SA-158, SA-177, SA-178, SA-179, and SA-180 (F-4, B-4, F-6, E-6, and C-6) provide overpressure protection at 250 psi.

The piping from the air receivers to valve SA-198 is normally pressurized. To start the diesel generator, solenoid valve SA-192 is opened allowing air to flow through lower motor valve SA-8-2B-2 and upper motor valve SA-8-2B-1 to the top of air relay valve SA-196, opening SA-196. This allows air from the left side of diaphragm-operated air valve SA-198 to pressurize the top of the diaphragm and open the valve. When SA-198 is opened, air flows through the air line lubricator SA-7-2B and is applied to the upper and lower air motors to start the diesel. When the diesel reaches self-sustaining speed, SA-192 is dumped, air bleeds off the top of SA-196 until it shuts, and then SA-198 shuts.

5.4.2.2 Auxiliary Feedwater and Steam Generator Blowdown Systems

Figures 5-7 and 5-8 show portions of the auxiliary feedwater and steam generator blowdown systems. On figure 5-7, which is a copy of drawing 11405-M-253, Sheet 4, an interconnection arrow at grid location F-8 is labelled "To Steam Generator RC-2A." The arrow indicates the print number and grid location of the connecting piping. The direction of the arrow indicates the normal direction of fluid flow through the interconnecting piping. The interconnection arrow indicates that the continuation of this pipe can be found on drawing number 11405-M-253 (sheet 1) at grid location D-6. On Figure 5-8, which is a copy of a portion of drawing 11405-M-253 (sheet 1), the connecting piping can be seen entering steam generator RC-2A at grid location D-6.

The configuration of the piping, valves, and instrumentation on a P&ID is not determined by the physical configurations in the plant. The P&ID configurations are positioned by the artist as necessary to clearly depict flowpaths, components, and instrumentation connections. Isometric and/or construction drawings provide an accurate representation of the actual physical configuration of the piping and components.

Figure 5-7 shows piping identification numbers and construction drawing references. In grid location D-7, the feedwater piping has a 4-inch diameter and has characteristics that can be found by referencing piping specification FW-1600. The reader should refer to isometric drawing IC-343 and/or IC-344 for details regarding the exact piping dimensions, bends, and fittings used in this stretch of piping.

In the upper left hand corner of Figure 5-7, there is a dashed line indicating that some of the components are located in the containment building and others are located in the auxiliary building. At grid location F-8, there is a box labelled M-97, which symbolizes the penetration through which the piping passes as it enters the containment building.

On Figure 5-7, the diamond-shaped symbols containing numbers at grid locations E-7 and E-8, indicate the ASME classification for this piping. The diamond containing the numbers 2 and 3 near HCV-1107B indicates that piping and components of higher ASME classification (level 2) are required downstream of this symbol. Piping and components of lower ASME classification (level 3) are sufficient for upstream positions of the system. The rest of the diamonds in these grid locations are shaded black in one half and contain a number in the other half. Again, the side with the number indicates the ASME classification that must be met by the piping and components in that direction. The side with the black shading indicates that the piping and components in that direction do not have to meet any ASME classification requirements or specifications. See Figure 5-4 for further explanation of these symbols.

Again, refer to figure 5-7 at grid location E-8. Note that HCV-1107B is a diaphragm-operated gate valve shown in the closed posititon. The letters "HCV" in the valve number mean "hand control valve" and can be determined by referring to the symbol list in Figure 5-4. Other valve identifiers contain the letters "FCV" (flow control valve), "PCV" (pressure control valve, "TCV" (temperature control valve), etc.

On some P&IDs valves are identified as to their fail position upon loss of air pressure or loss of electrical power. The letters FO (fails open), FC (fails closed), or FAI (fails as is) are placed near the valve operator.

5.5 One-Line Electrical Diagrams and Control Wiring Diagrams

Electrical systems are usually composed of conductors and many power circuit devices such as circuit breakers, transformers, meters, relays, and fuses installed in one or more lines. This is illustrated in the simple circuit shown in Figure 5-9, called an elementary electrical diagram or three-line diagram. This figure shows the details of the electric power circuit for a motor, which allows the current paths to be traced through all conductors and components in the circuit.

Three-line diagrams become very complex and difficult to read when several power supplies and loads are included. Therefore, a simplified version, called a one-line electrical diagram, is often used when the purpose is to represent the path of energy transfer (as opposed to the current paths) between sources and loads. This course deals almost exclusively with one-line electrical diagrams.

5.5.1 Purposes

One-line electrical diagrams are used to describe the paths available from power supplies to loads. These diagrams are usually used to determine one or more of the following:

- The power source to a component,
- The prerequisites for energizing or deenergizing a component,

- The sequence of events when a control switch is repositioned, and
- The location of one component with respect to another component.

5.5.2 Symbols and Notation

Like P&IDs, one-line electrical diagrams use symbols and notations to represent components in a system and to show the physical relationships between components. The following information is usually included on one-line diagrams:

- Manufacturer's type designations and ratings of devices,
- Transformer identification numbers and ratios,
- Power transformer connection types (ie, wye, delta),
- Circuit breaker ratings in volts and amperes,
- Switch and fuse ratings in volts and amperes,
- Relay functions (device function numbers),
- Voltage, phase and frequency of all buses, and
- Size and type of cables.

To interpret the information provided on these diagrams, operators must be familiar with the legend, which describes the symbols and notation used on the diagram. A typical legend is shown in Figure 5-10. Additionally, Appendix A at the end of this chapter provides a list of standard device numbers used throughout the industry in one-line electrical diagrams. For example, 51 is the standard device number for an AC overcurrent relay, therefore, all the contacts associated with this type of relay would be identified with the prefix or suffix 51.

Circles are used to represent meters, relays, indicating lights, and motors in the legend. Usually these devices can be differentiated by their location in the circuit; however, the following list of abbreviations is also used for identification.

<u>Meter Abbreviations</u>:

- A - Ammeter
- PH - Phase meter
- AH - Ampere-hour meter
- SYN - Synchroscope
- CRO - Oscilloscope
- TD - Transducer
- DM - Demand meter
- V - Voltmeter
- F - Frequency meter
- VA - Volt-ammeter
- GD - Ground detector
- VAR - Varmeter
- OHM - Ohmmeter
- VARH - Varhour meter
- OSC - Oscillograph
- W - Wattmeter
- PF - Power factor
- WH - Watthour meter

<u>Relay Abbreviations</u>:

CC - Closing coil

- TD - Time delay relay

CR - Closing/control relay

- TDE - Time delay energize

TC - Trip coil

- TDD - Time delay de-energize

TR - Trip relay

- X - Auxiliary relay

Indication lamp abbreviations:

A - Amber	G - Green
B - Blue	R - Red
C - Clear	W - White

Motors usually have their horsepower rating, abbreviated HP, in or near the circle.

Standard abbreviations for different types of contacts and switches are indicated below. All contacts included in one-line diagrams are shown in the position they would be in with their associated relay deenergized.

a - Breaker "a" contact	PB - Pushbutton
b - Breaker "b" contact	PS - Pressure switch
BAS - Bell alarm switch	PSD - Differential pres. switch
BLPB - Backlighted pushbutton	TDO - Time delay open
CS - Control switch	TDS - Time delay shut
FS - Flow switch	TS - Temperature switch
LS - Level switch	XSH - Auxiliary switch

"a" and "b" contacts usually refer to contacts that have their positions determined by the position of an associated breaker. "a" contacts are open when the associated breaker is open and closed when the breaker is closed. "b" contacts are closed when the associated breaker is open and open when the breaker is closed.

Similarly, contacts operated by relays are typically shown on electrical drawings as being in the condition (open or closed) associated with the relay being deenergized. If the relay is subsequently energized, the associated contacts will change to the opposite condition.

To avoid confusion, the junctions between two conductors must be very clearly identified in one-line electrical diagrams. Two wires that simply cross one another do not form a junction. Junctions are normally indicated by two wires crossing with a large solid dot drawn at their intersection. This symbol is shown in the lower left hand corner of Figure 5-10.

5.5.3 Examples

The following sections discuss examples of different types of electrical diagrams.

5.5.3.1 Breaker Control Circuits

One of the most common types of one-line electrical diagrams are control wiring diagrams. These diagrams describe the system conditions required for a circuit breaker to open or shut, or for a motor to be energized or de-energized. Figure 5-11 shows the control wiring diagram for a diesel generator tie breaker T1.

The position of breaker T1 is determined by a control switch located in a remote location. The breaker control switch has three positions—close, trip, and neutral. The switch spring returns the switch to the neutral position upon release by the operator. The diagram in the lower right hand corner of Figure 5-11 describes the position of the control switch contacts for every position of the control switch. For example, contact 3 is shut only when the control switch is held in the close or trip position, while contact 7 is shut while the switch is held in the close position and after it is allowed to spring return from close to the neutral position.

To close breaker T1, the closing coil (CC) must be energized by the 125 V DC power supply. This occurs when contacts 24AX-2 and 24AX-3 are shut to provide a complete path for current flow from the positive terminal of the 125 V DC power supply on the top of the diagram, through 24AX-2, through the closing coil, through 24AX-3, and back to the negative terminal of the 125 V DC power supply on the bottom of the diagram. Since contacts are always shown with their associated relay de-energized, relay 24AX must be energized to shut contacts 24AX-2 and 24AX-3. Therefore, to energize the closing coil and shut breaker T1, a complete path for current flow must be provided from the 125 V DC power supply through either relay 24AX-HC or 24AX-PC.

When the control switch is placed in the close position, contacts CS/1B-3 and CS/1B-4 (near the top of the diagram) shut. Contacts 52b-G1 and 52b-G2 are shut only when breakers G1 and G2 are open, because they are both "b" contacts. These contacts ensure that at least one of these breakers (G1 or G2) is open before T1 can be closed. Contact 24A-IS is shut unless the T1 breaker is racked out for maintenance. Therefore, relay 24AX-HC and the closing coil will be energized and breaker T1 will shut if the control switch is taken to the close position, and provided breaker T1 is not racked out for maintenance.

When breaker T1 shuts, the 24b-T1 contact opens, de-energizing the green, breaker open, indicating light, and both 24a-T1 contacts shut, energizing the red, breaker closed, indicating light, and preparing the trip coil (24A-TC) to be energized.

The trip coil is energized and the breaker is opened if the control switch is taken to the trip position, shutting contact CS1B-2, or if either overcurrent relay contact (51/CO) closes due to excessive current flow through breaker T1.

5.5.3.2 Electrical Distribution System

Another common use of the one-line electrical diagram is for plant electrical distribution systems. Figure 5-12 shows a simplified one-line diagram of a plant electrical distribution system. Figure 5-13 is a more detailed version of a one-line diagram.

The distribution system diagram describes the power flow path from the source to each of the major switchboards. It includes all major electrical components (generators, transformers, circuit breakers, disconnects, and electrical buses) and is arranged to minimize the number of crossing lines. It does not accurately portray the physical arrangement of the components. Two loads powered from the same bus may be located hundreds of feet from each other, but are shown close together on the one-line diagram.

5.6 Logic Diagrams

Logic diagrams are used to describe the conditions required for automatic operation of system components. The automatic operation of system components is also referred to as control function. For example, if reactor power is too high, a control function causes the reactor to scram automatically. Logic diagrams are usually used by operators for one or more of the following reasons:

- Determine which systems provide inputs to a control function;
- Determine how many instruments must fail before a control function is either caused or prevented;
- Determine how many instruments must detect an out of specification condition to cause a control function to occur; and
- Determine the maximum or minimum system conditions allowed before a control function occurs.

5.6.1 Logic Diagram Symbols

The symbols used in logic diagrams represent the logic devices, which are normally called logic gates. Figure 5-14 shows the common AND, OR, and NOT logic gates. These are the most commonly used symbols in commercial power plant logic diagrams. Figure 5-14 also shows the symbol for a retentive memory device. Additional logic diagram symbols are explained on Figure 5-15. Figure 5-16 shows a portion of a typical logic diagram legend.

As shown in Figure 5-14, the output of a logic gate is determined by the combination of inputs. A NOT gate is the simplest of the logic gates. The output of a NOT gate is always the opposite of the input.

The output of an OR gate will be a "1" if any of the inputs are a "1." No matter how many input lines there are to an OR gate, if one or more of the inputs are a "1," the output will be a "1."

The output of a simple AND gate will be a "1," if <u>all</u> of the inputs are "1's." If any of the inputs to a simple AND gate are "0", the output is "0."

In some logic diagrams, AND gates are shown with two numbers, such as 2/4, inside the gate symbol. The output of this type of AND gate will be a "1" if <u>any 2</u> of the 4 inputs are "1's." This type of gate is still called an AND gate because multiple inputs must be a "1" to have a "1" output. This gate is often called <u>coincidence logic</u> because multiple, but not all, inputs have to be present at the same time to produce an output from the gate.

A variation on coincidence logic is the selective 2 out of 4 logic, also known as 1 out of 2 taken twice. In this logic, the 4 inputs are divided into 2 pairs, each with an OR gate whose output is combined in a normal AND gate. Normally each pair has a separate power supply. At least one input for each pair must be present to produce an output from this logic. This <u>selective coincidence logic</u> prevents a false output being caused by a transient on a single power supply.

The output of a retentive memory logic gate is determined by the last input to receive a "1." The input circuits for these gates are arranged such that the gates never receive a "1" from both inputs at the same time. Therefore, their output is always determined by the last input to be a "1." Retentive memory gates also remember their last input signal even if power is lost to the circuit; they restore the appropriate output when power is restored.

5.6.2 Logic Diagram Examples

The following sections discuss examples of different types of logic diagrams.

5.6.2.1 Simplified Reactor Trip

Figure 5-17 shows a simplified version of a reactor trip logic diagram. The circuit will cause an automatic scram of the reactor if certain plant conditions occur.

Often the easiest way to analyze a logic diagram is to work backward from the final output. In Figure 5-17, a reactor trip will occur if any of the inputs to the bottom OR gate are "1's." Except for the "Other trip signals" input, all of the inputs to this OR gate come through the row of AND gates just above the OR gate. The output of the AND gates will be a "1" if the output from the P-7 Permissive Logic circuit is a "1" and if any of the following conditions are true:

- Two of four reactor coolant pump undervoltage signals are received.
- Two of four reactor coolant pump underfrequency signals are received.
- A turbine trip signal is received.
- Either two of four reactor coolant pump breakers are open, or two of four reactor coolant system low flow signals are received.
- Two of three pressurizer high level signals (greater than 92%) are received.
- Two of four pressurizer low pressure signals (less than 1970 psig) are received.

Finally, the output of the P-7 Permissive Logic circuit will be a "1" if either of the following conditions are true:

1. Two of the four nuclear instrumentation power range signals are greater than 10%.

2. Either of the two turbine first stage steam pressure signals are greater than 10%.

The purpose of the P-7 Permissive Logic circuit is to prevent inadvertent reactor scrams due to this circuitry when the reactor is being started up (ie. less than 10% power or 10% pressure in the turbine first stage).

5.6.2.2 Detailed Reactor Trip and Safety Injection

Figure 5-18 is a detailed logic diagram for several pressurizer pressure functions. It shows the inputs from the pressurizer instrument systems to the reactor trip and safety injection functions. The pressurizer low pressure logic shows more detailed portions of the simplified logic diagram presented in Figure 5-17.

In the pressurizer low pressure diagram, two of four signals from the instrument bistables and a signal from the P-7 circuitry (which is shown on Figure 5-18) produce a signal for a reactor trip. As described in the legend (see Figure 5-16), the larger circles with PB and a number represent pressure bistables. The C in a square represents a computer input from the bistable, the T in the circle represents a trip status indicator light, and the A in a triangle represents an alarm annunciator. The "step down" located to the right of each low pressure bistable indicates that the bistable output will be a "1" when the pressure decreases below the setpoint. The "step up" located to the right of the 3 pressure bistables indicates that the bistable output will be a "1" when level increases above a setpoint.

Note the AND logic gate with three inputs, two of which come from the pressurizer SI block control. If the operator places the block control switch in BLOCK, a "1" will be sent to the AND logic gate via an OR logic gate. If the other inputs to the AND logic gate are "1," the output will be a "1." The NOT logic gate will produce a "0" output thereby preventing (or blocking) a safety injection. The block signal is "sealed in" by the OR logic gate because it receives an input from the output of the AND logic gate.

5.7 Summary

This chapter has provided an introduction to print reading. There are several different types of prints including P&IDs, one-line electrical diagrams, and logic diagrams. Each diagram serves a different purpose and provides users with different types of information. To fully understand the plant systems and their operation, personnel must be able to locate, recognize, and interpret information available on these diagrams.

Each plant maintains their diagrams in a different manner and may use slightly different symbols and numbering systems; however, each set of prints contains a legend that should always be used to clarify any doubts or uncertainties. The fundamentals presented in this chapter apply to the majority of prints in the industry.

DRAWING NO.	DESCRIPTION
11405-M-254	Condensate P&ID
11405-M-255	Heater Drains P&ID
11405-M-256	Heater Vents P&ID
11405-M-257	Circulating Water P&ID
11405-M-258	Turbine Plant Cooling water P&ID
11405-M-259	Potable and Service Water P&ID
11405-M-260.Sh.1	Aux. Steam and Condensate Return P&ID
11405-M-260.Sh.2	Aux. Steam and Condensate Return P&ID
11405-M-260.Sh.3	Aux. Steam and Condensate Return P&ID
11405-M-260.Sh.4	Aux. Steam and Condensate Return P&ID
11405-M-260.Sh.5	Aux. Steam and Condensate Return P&ID
11405-M-261	Condenser Evacuation and H_2/CO_2 Piping P&ID
11405-M-262.Sh.1	Fuel Oil P&ID
11405-M-262.Sh.2	Turbine Lube Oil P&ID
11405-M-262.Sh.3	Fuel Oil System FP, Security and TSC Diesels
11405-M-263	Compressed Air P&ID
11405-M-264.Sh.1	Instrument Air Diagram Auxiliary Building and Containmen
11405-M-264.Sh.2	Instrument Air Diagram for Turbine Building and Intake
11405-M-264.Sh.3	Instrument Air Diagram Riser Details
11405-M-264.Sh.4	Instrument Air Diagram Riser Details
11405-M-264.Sh.5	Instrument Air Diagram Riser Details
11405-M-265	Miscellaneous Drains and Chemical Feed P&ID
11405-M-266.Sh.1	Fire Protection P&ID
11405-M-266.Sh.8	Fire Protection Deluge System Details
11405-M-266.Sh.9	Fire Protection Deluge System Details
11405-M-267	Vacuum Priming P&ID
Figure 8.1-1	Simplified One-Line Diagram Plant Electrical System
627-D-8053	Aqua-Chem Model RW-900 SP
C-4175, Sh.1	Typical Control Valve Air Source Valve Configurations
C-4175, Sh.2	Control Valve Air Source Valve Lineup/ Listing
D-4878	Reactor Coolant Gas Vent System
D-23866-210-111.SH.1	Reactor Coolant Pump RC-3A
D-23866-210-111.SH.2	Reactor Coolant Pump RC-3B
D-23866-210-111.SH.3	Reactor Coolant Pump RC-3C
D-23866-210-111.SH.4	Reactor Coolant Pump RC-3D
E-23866-210-110	Reactor Coolant System
E-23866-210-120, Sh.1	Chemical and Volume Control
E-23866-210-120, Sh.2	Chemical and Volume Control
E-23866-210-121	Chemical and Volume Control
E-23866-210-130, Sh.1	Safety Injection and Containment Spray
E-23866-210-130, Sh.2	Safety Injection and Containment Spray
949 D 151	Gas Control Piping Diagram
949 D 154	Arrangement of Shaft Sealing System
738E345	Diagram of Steam Seal Piping
234 R 311	Stator Winding Cooling Water System
4770-435-302-001	Steam Generator Blowdown Processing System P&ID
4770-769-902-001	Building Services Technical Support Center HVAC P&ID
B120F03001.Sh.1 & 2	Lube Oil System Schematic
B120F04002, Sh.1 & 2	Jacket Water Schematic
B120F07001.SH.1	DG-1 Air Starting System Schematic
B120F07001.SH.2	DG-2 Air Starting System Schematic
13007.54-EM-1A-10	Post Accident Sampling System NUREG 0737 Section II.B.3

Figure 5-1. Partial Print Index

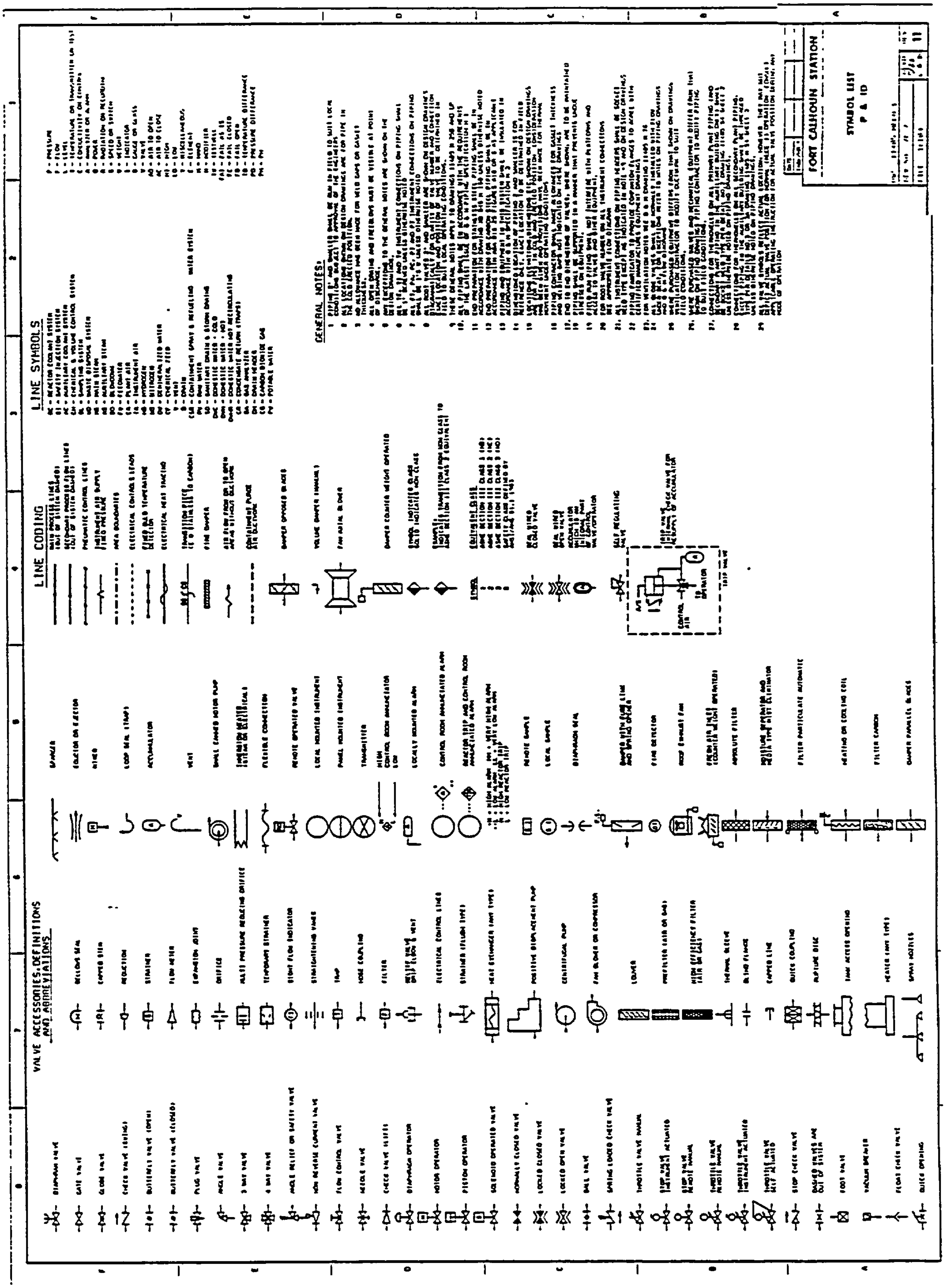


Figure 5-2. Typical P&ID Symbol List

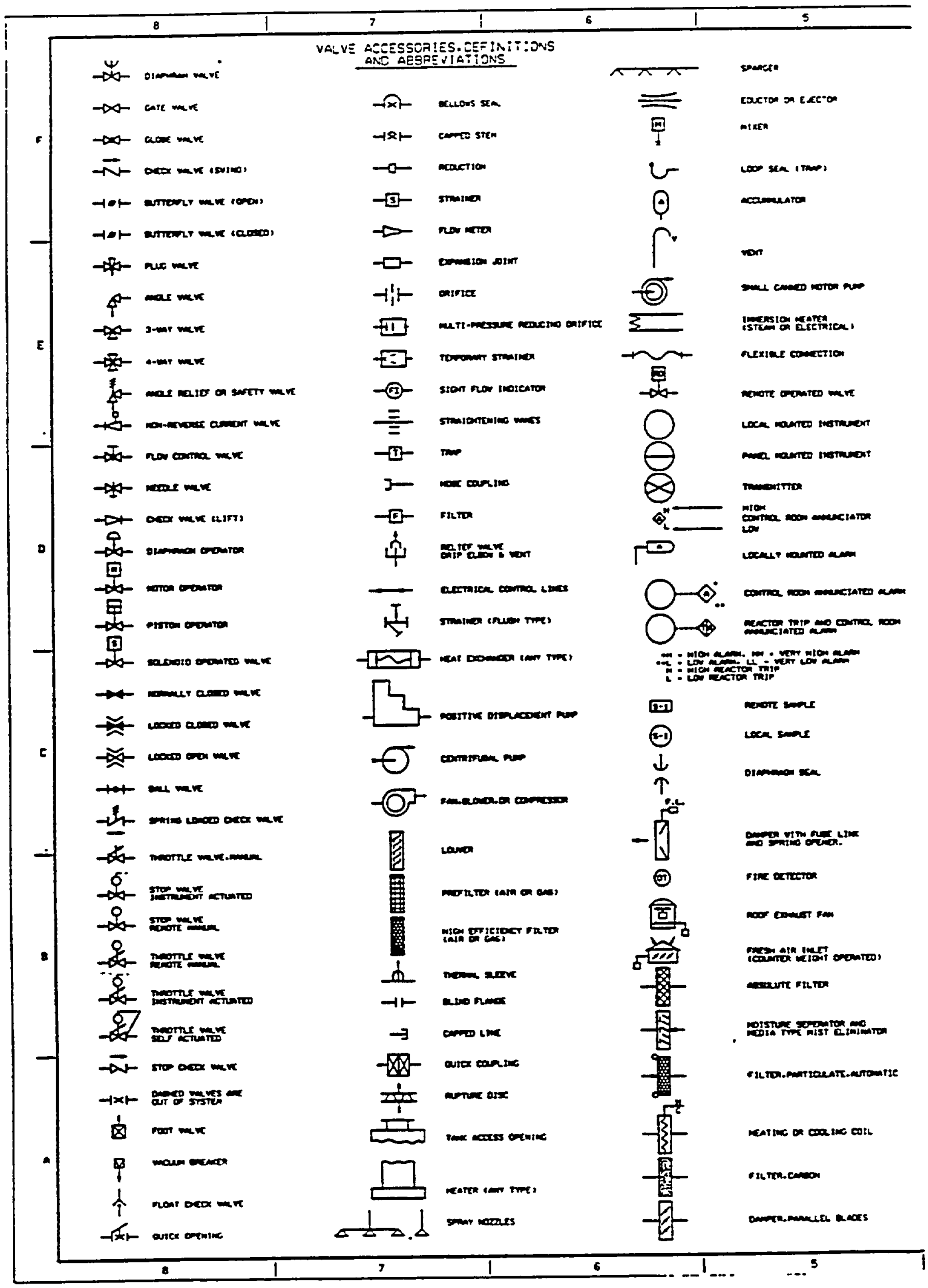


Figure 5-3. P&ID Symbol List - Part 1

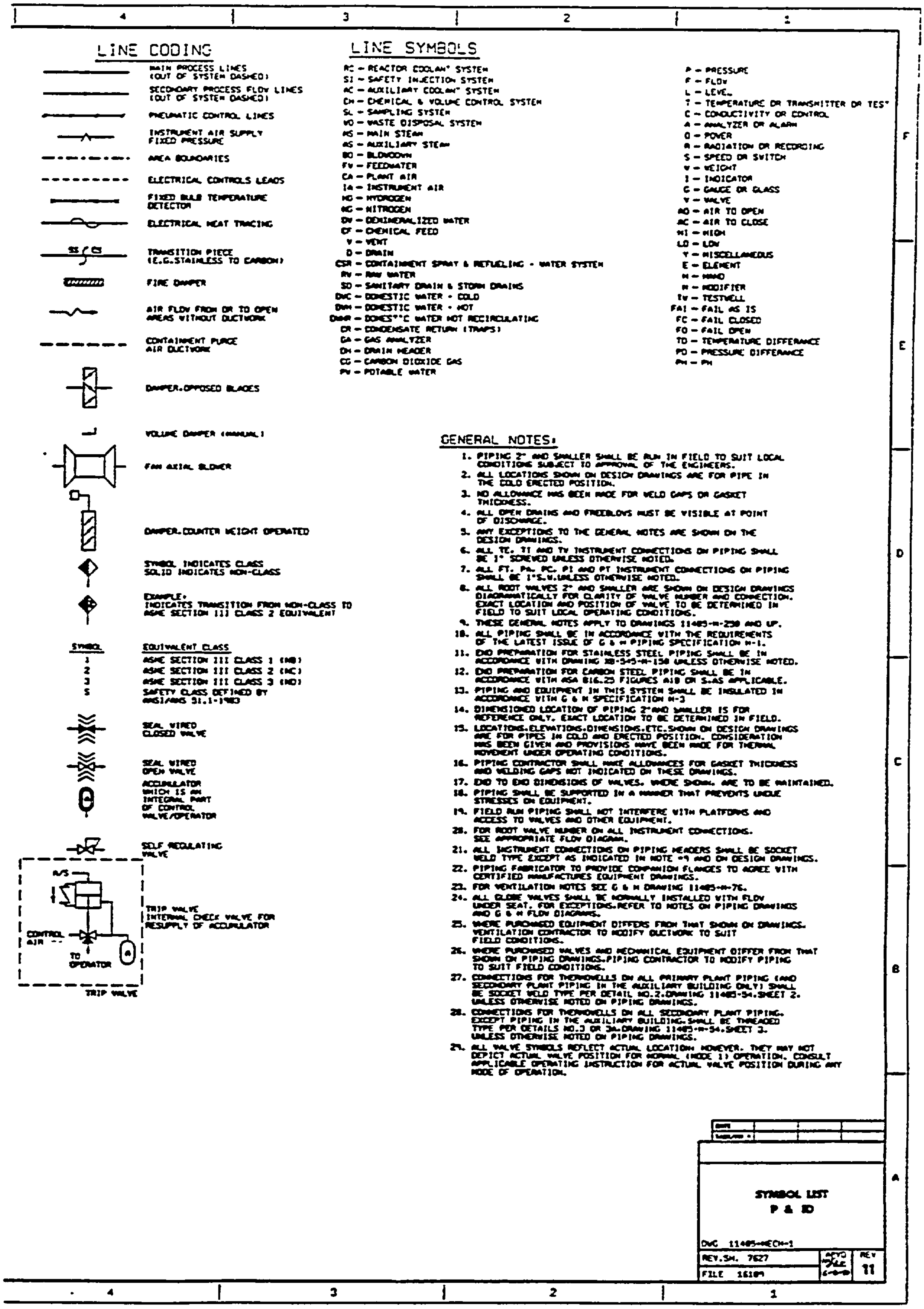


Figure 5-4. P&ID Symbol List - Part 2

Air Start System

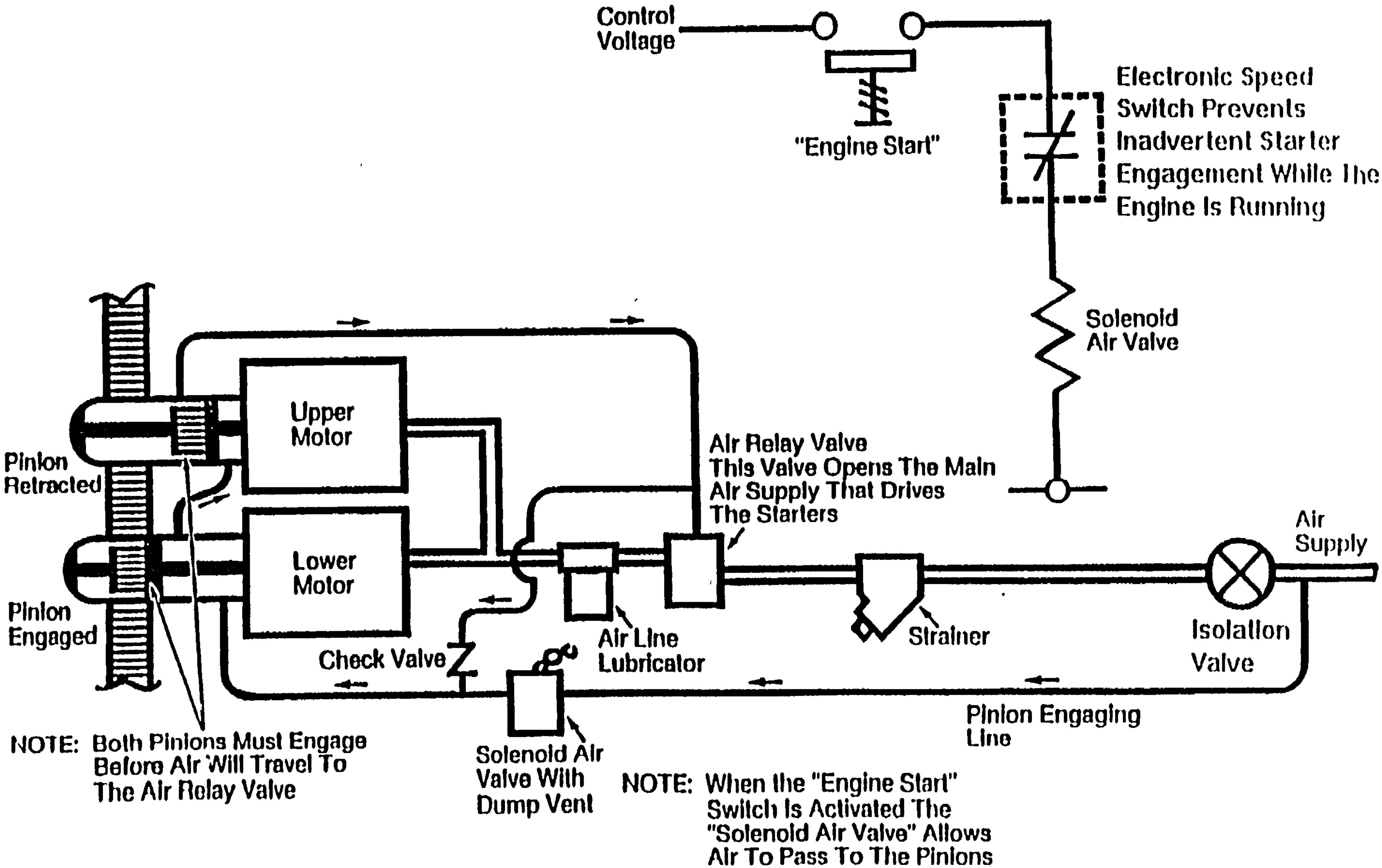


Figure 5-5. Diesel Air Start System Sketch

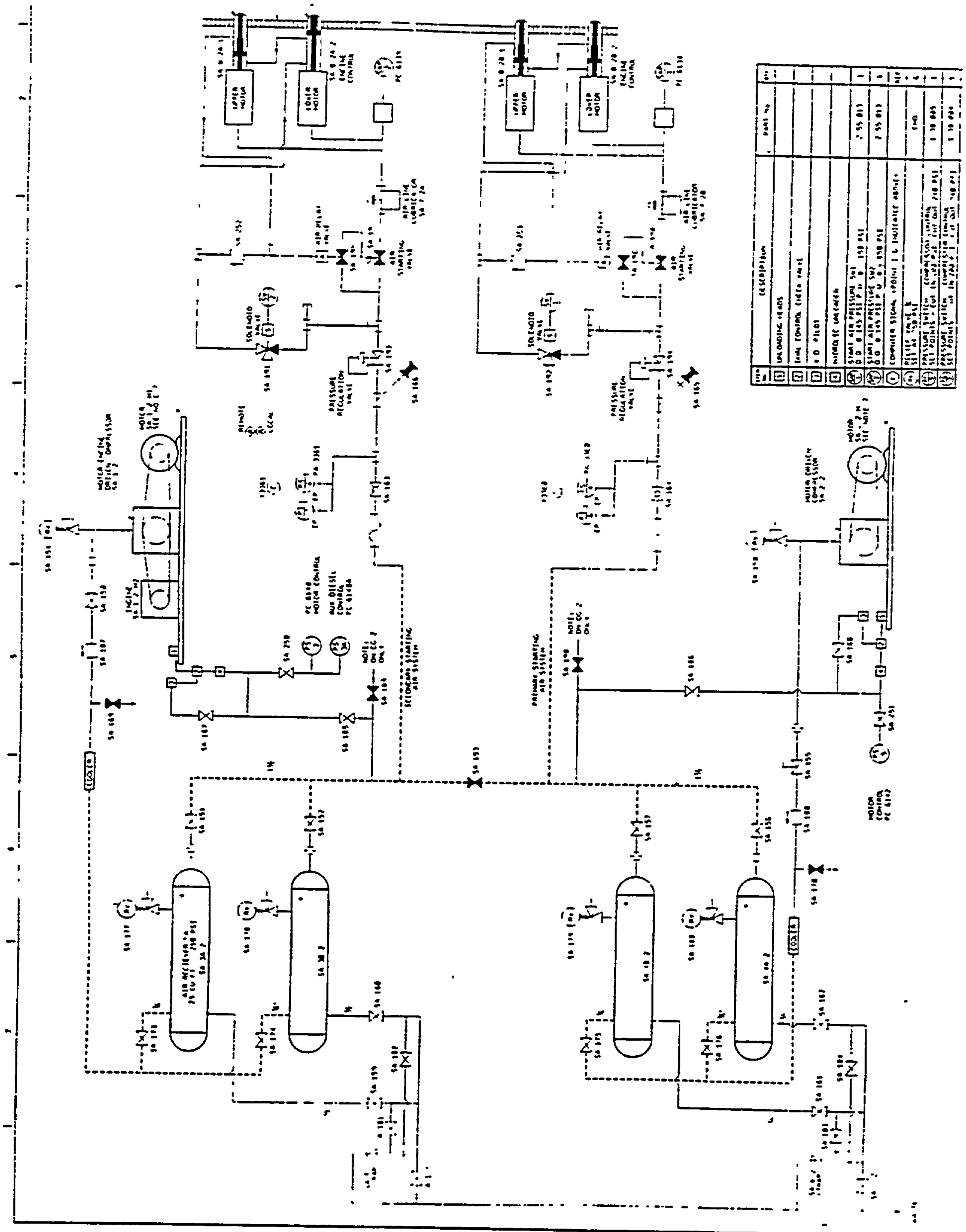


Figure 5-6. Diesel Air Start System P&ID

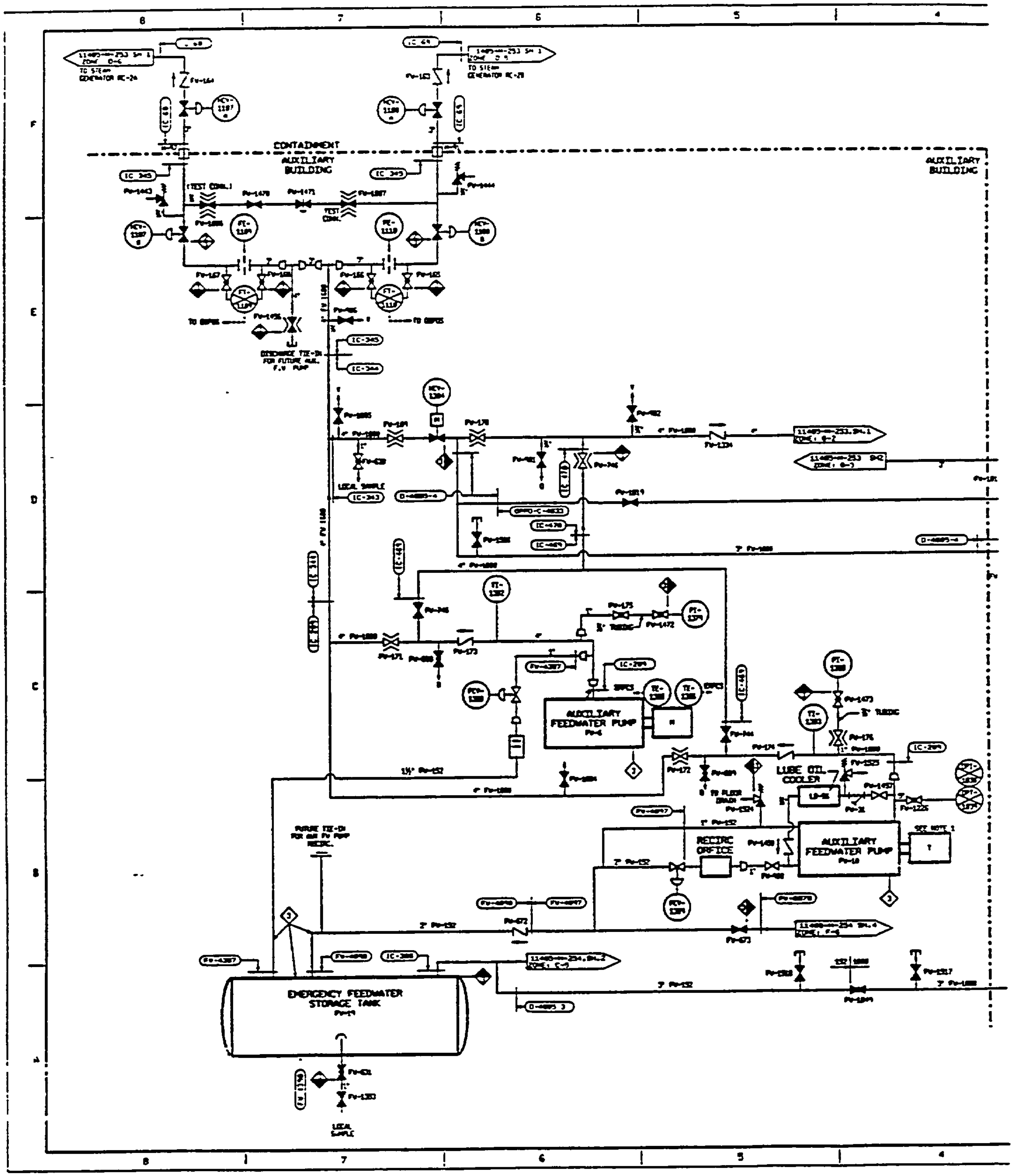


Figure 5-7. Auxiliary Feedwater and Steam Generator (Partial)

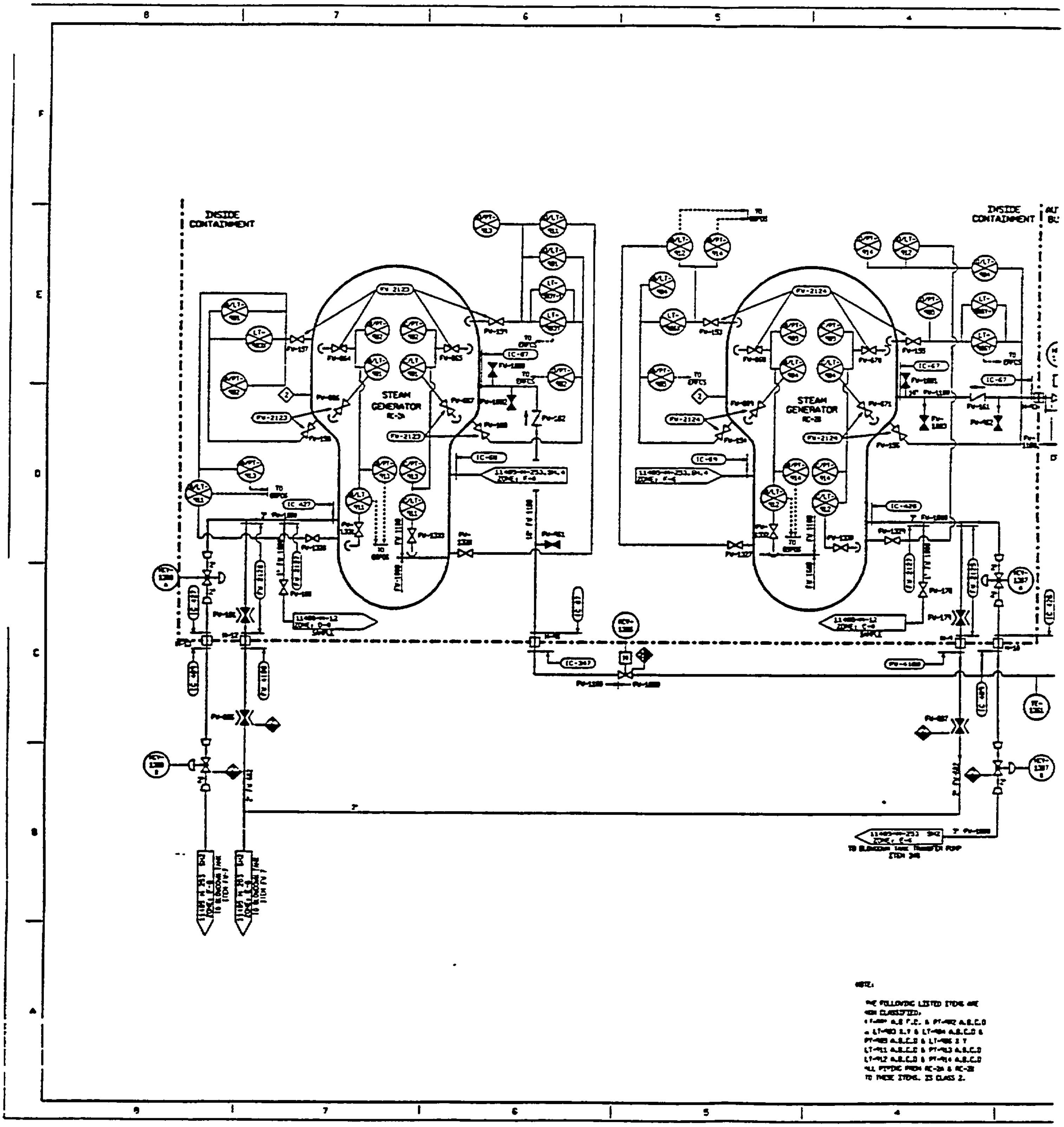
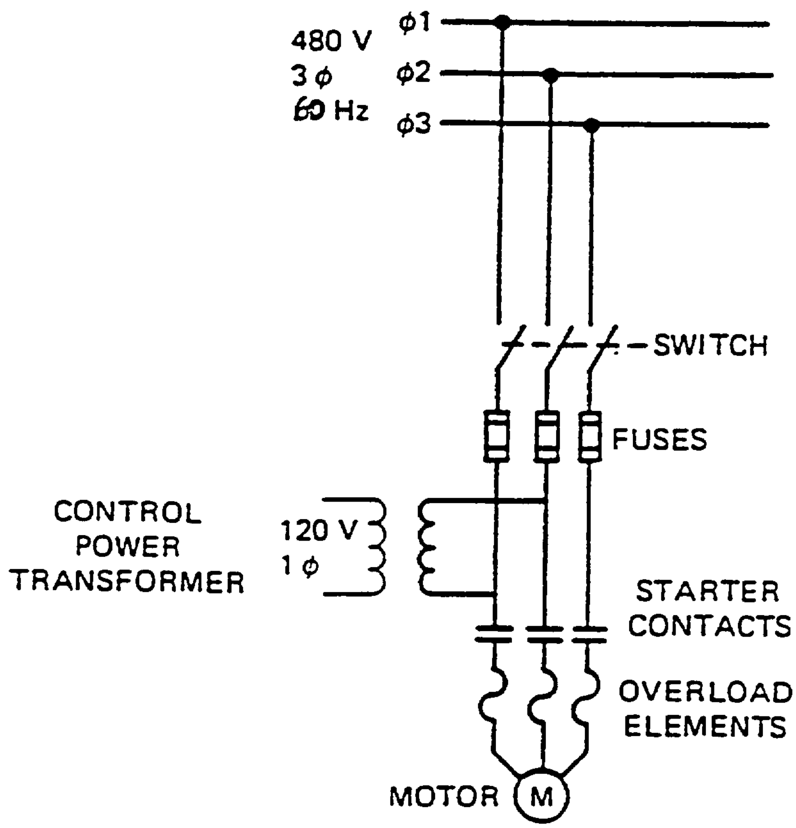


Figure 5-8. Auxiliary Feedwater and Steam Generator Blowdown Systems (Partial)



PPF-TP-4.19

Figure 5-9. Elementary Electrical (Three-Line) Diagram

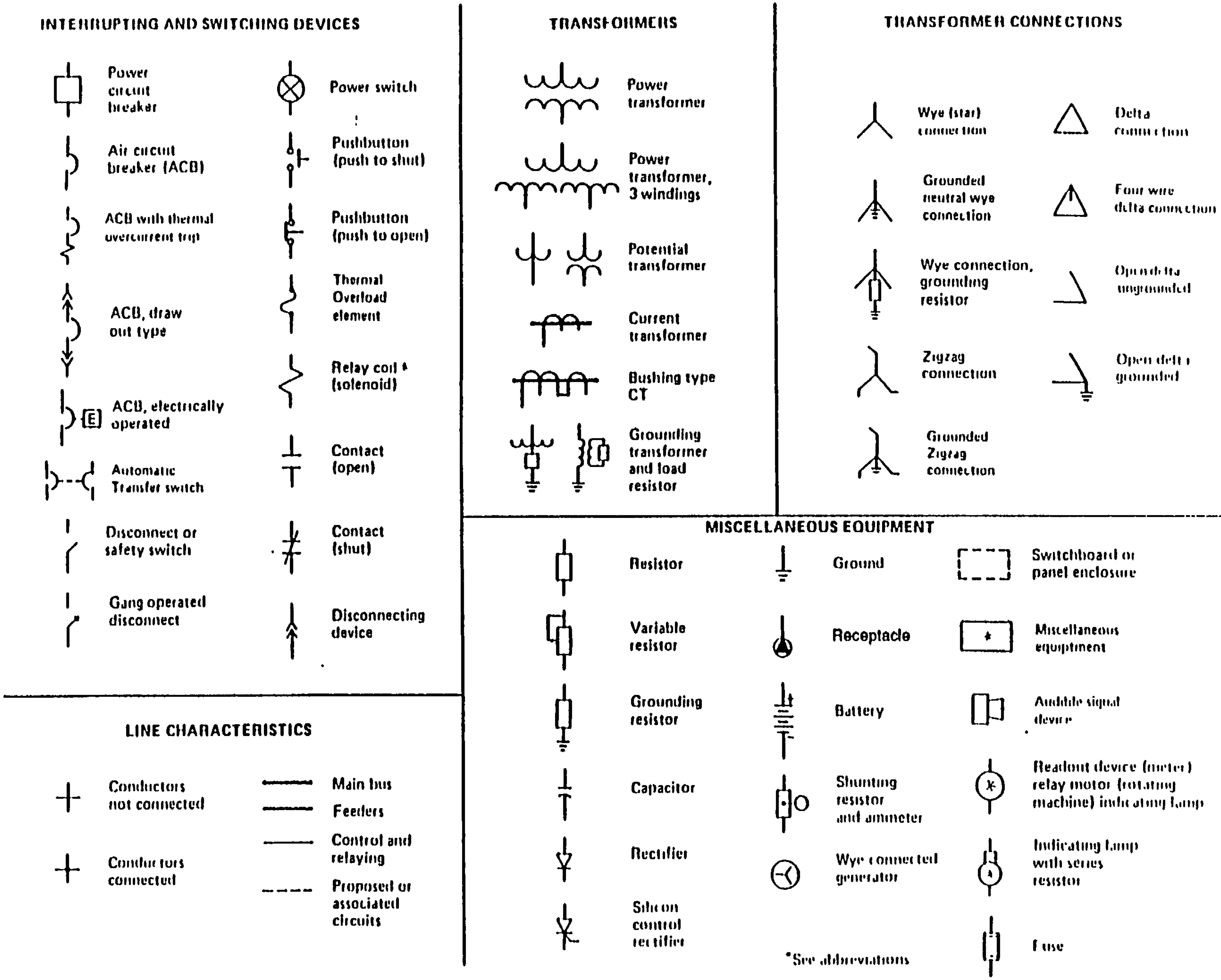
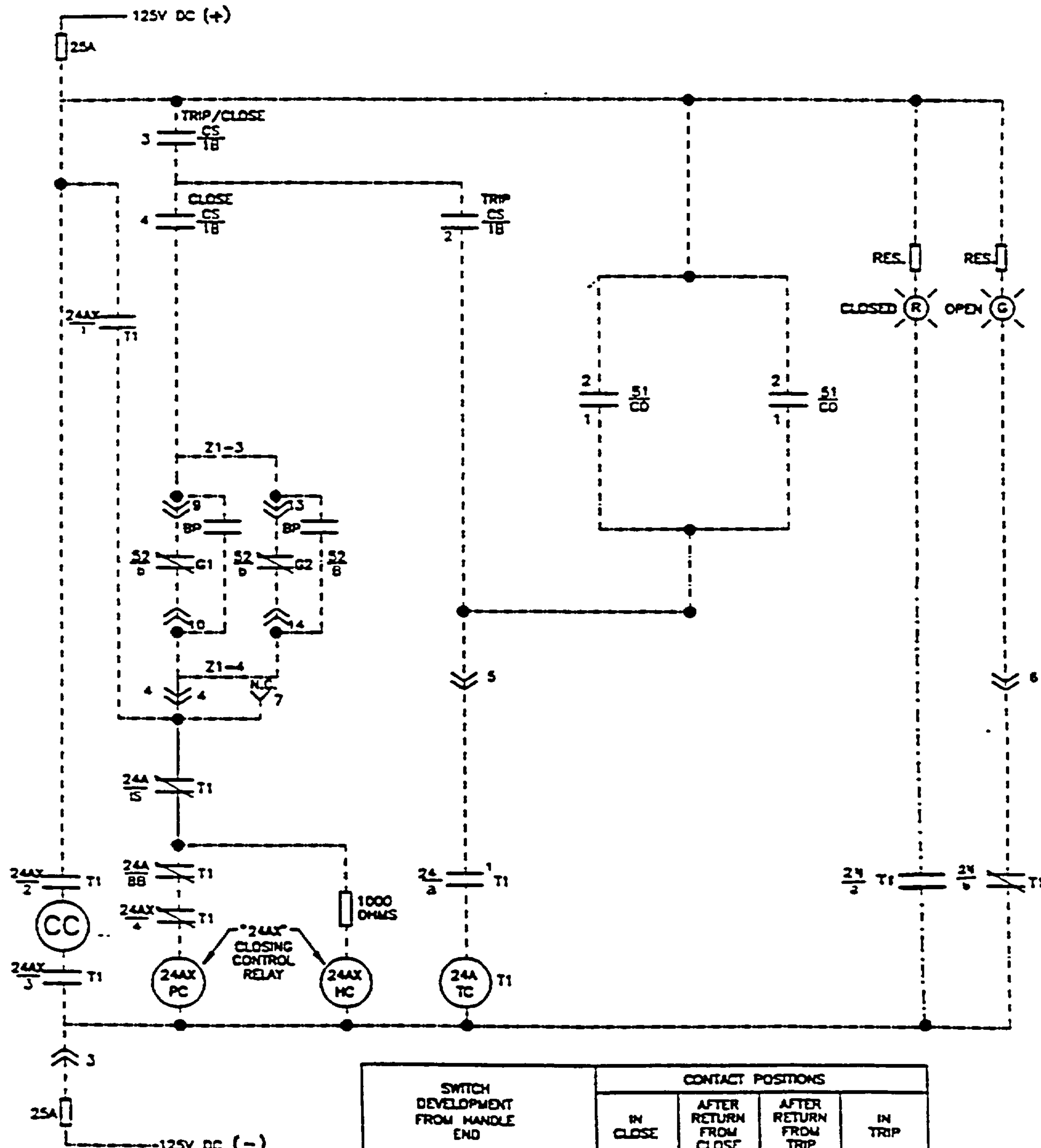


Figure 5-10. Typical One-Line Diagram Legend

BREAKER T1 CONTROL CIRCUIT



SWITCH DEVELOPMENT FROM HANDLE END		CONTACT POSITIONS			
		IN CLOSE	AFTER RETURN FROM CLOSE	AFTER RETURN FROM TRIP	IN TRIP
	1	X			
	2				X
	3	X			X
	4	X			
	5		X	X	
	7	X	X		
	8	X	X		

CONTROL SWITCH SYMBOLS

Figure 5-11. Diesel Generator Tie Breaker Control Wiring Diagram

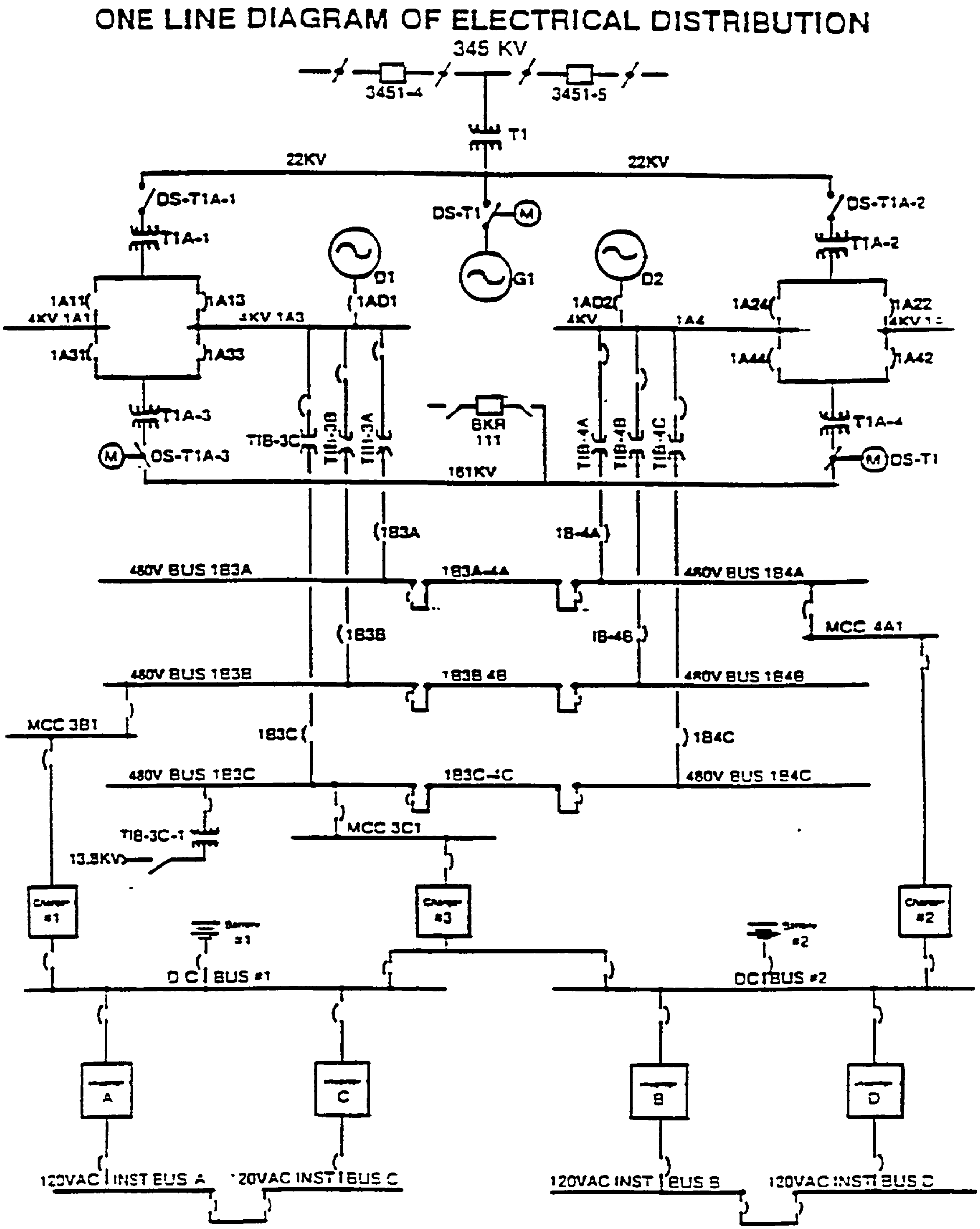


Figure 5-12. Electrical Distribution System Sketch

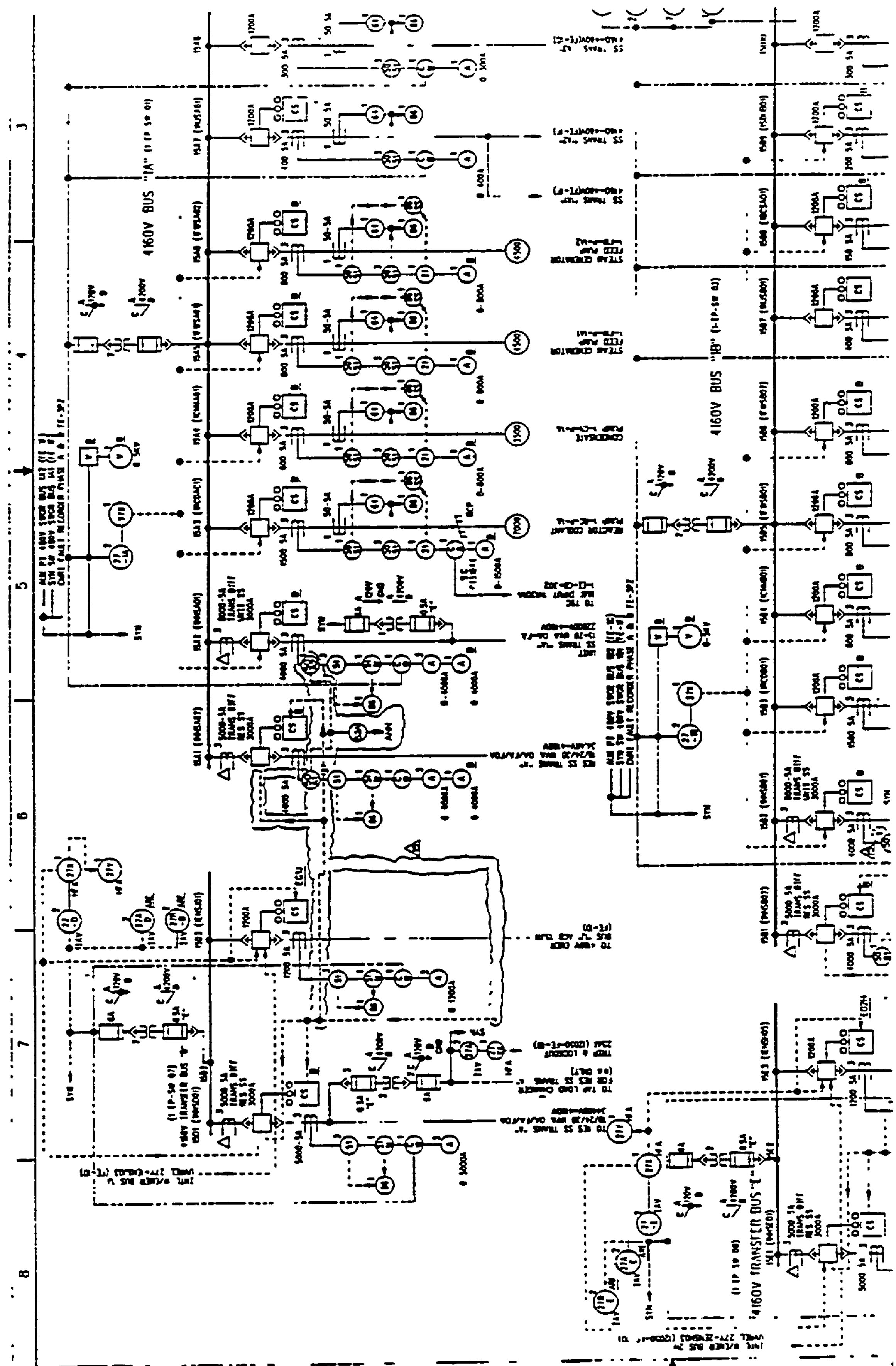
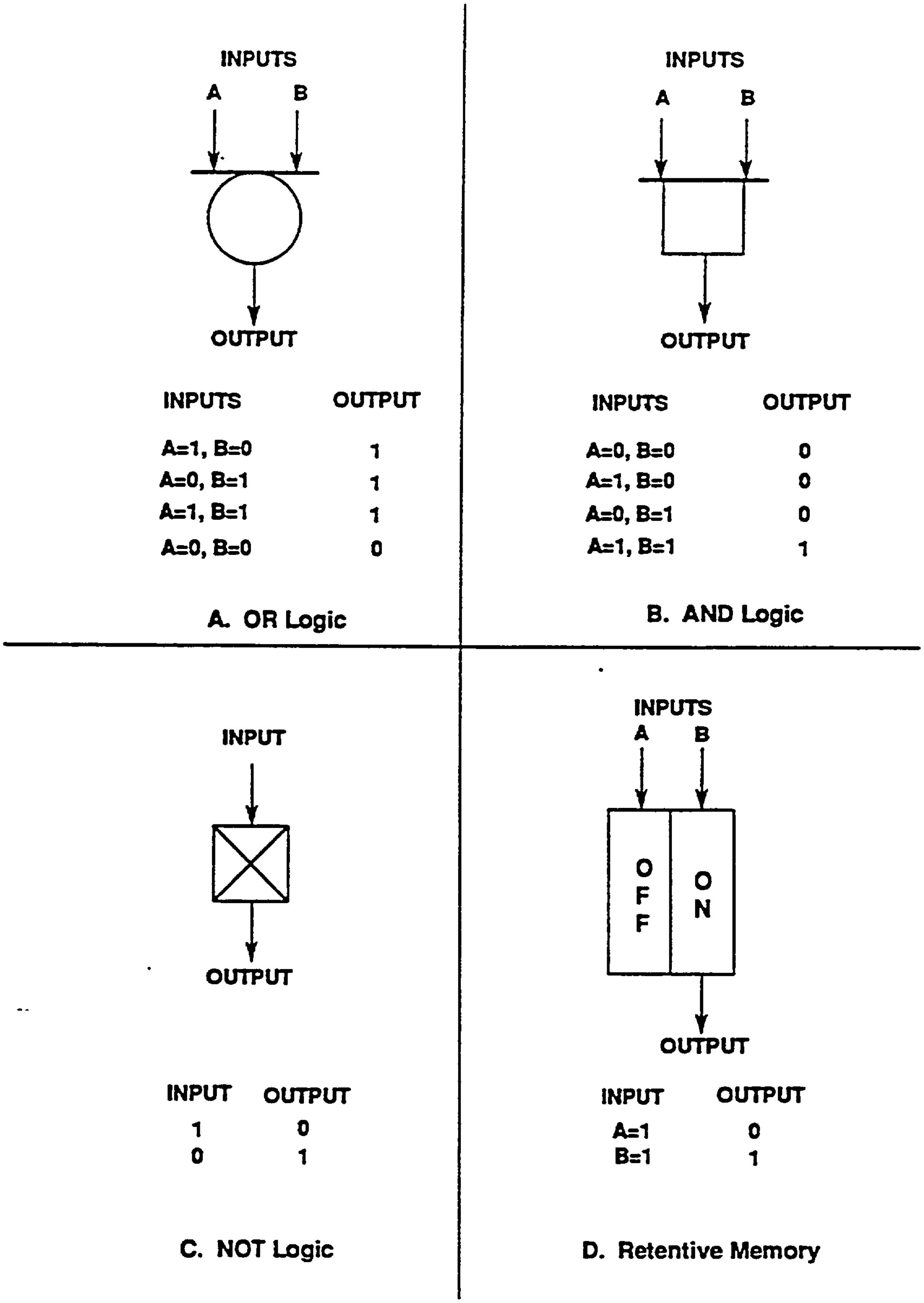


Figure 5-13. Electrical Distribution System One-Line Diagram



INPUTS	OUTPUT
A=1, B=0	1
A=0, B=1	1
A=1, B=1	1
A=0, B=0	0

A. OR Logic

INPUTS	OUTPUT
A=0, B=0	0
A=1, B=0	0
A=0, B=1	0
A=1, B=1	1

B. AND Logic

INPUT	OUTPUT
1	0
0	1

C. NOT Logic

INPUT	OUTPUT
A=1	0
B=1	1

D. Retentive Memory

Figure 5-14. Logic Functions

ALARM LIGHT	
COMMON	A
REACTOR TRIP	R
TURBINE TRIP	T
BISTABLE	
PRESSURE BISTABLE	PB
HAS OUTPUT WHEN INPUT EXCEEDS SETPOINT	
HAS OUTPUT WHEN INPUT IS BELOW SETPOINT	
COMPUTER INPUT	C OR C
DISPLAY	
INDICATOR	I
RECORDER	R
STATUS LIGHT	
ACTUATION	A
BYPASS	B
PERMISSIVE	P
TRIP	T

Figure 5-15. Miscellaneous Logic Diagram Symbols

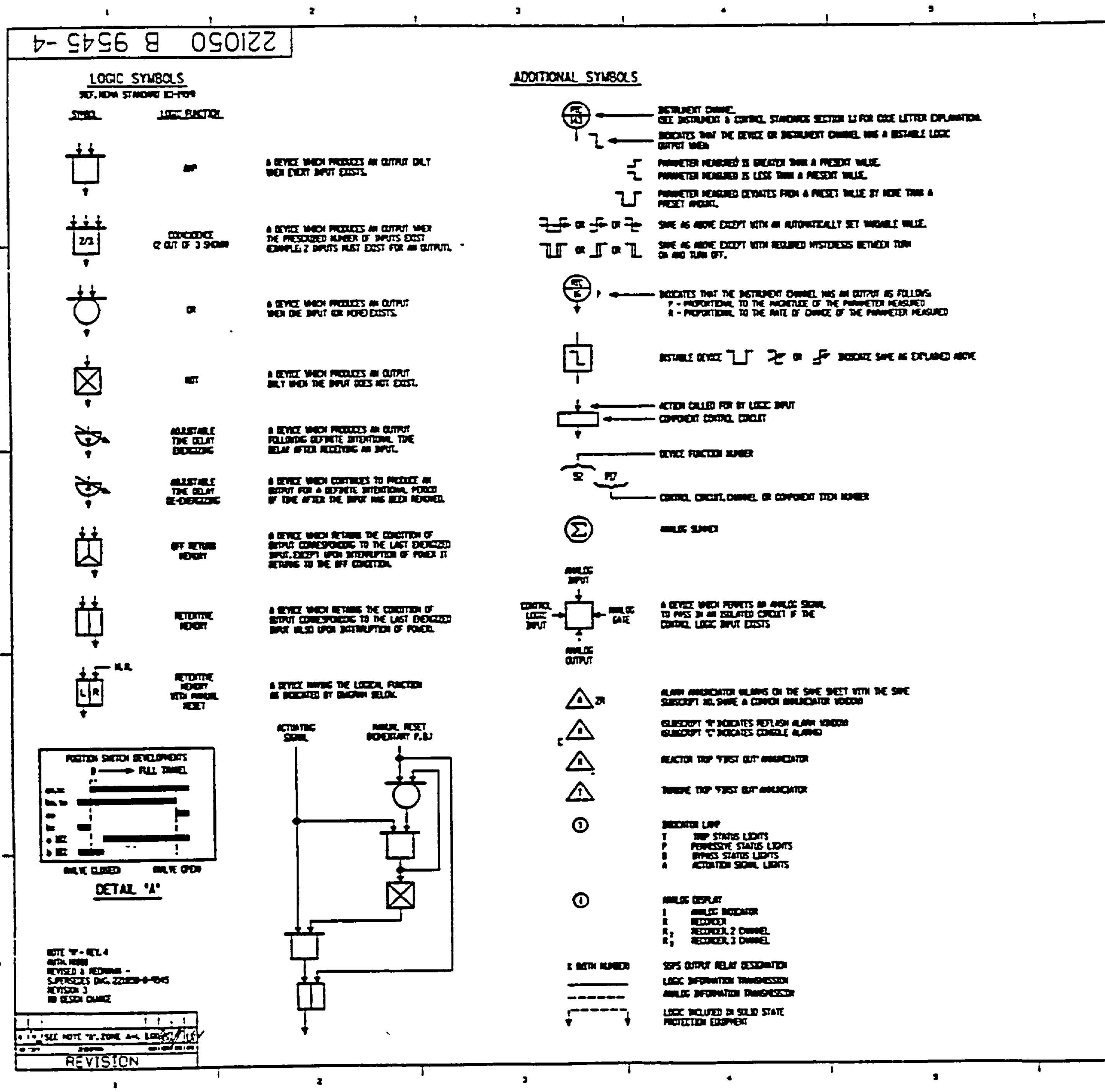


Figure 5-16. Typical Logic Diagram Symbols

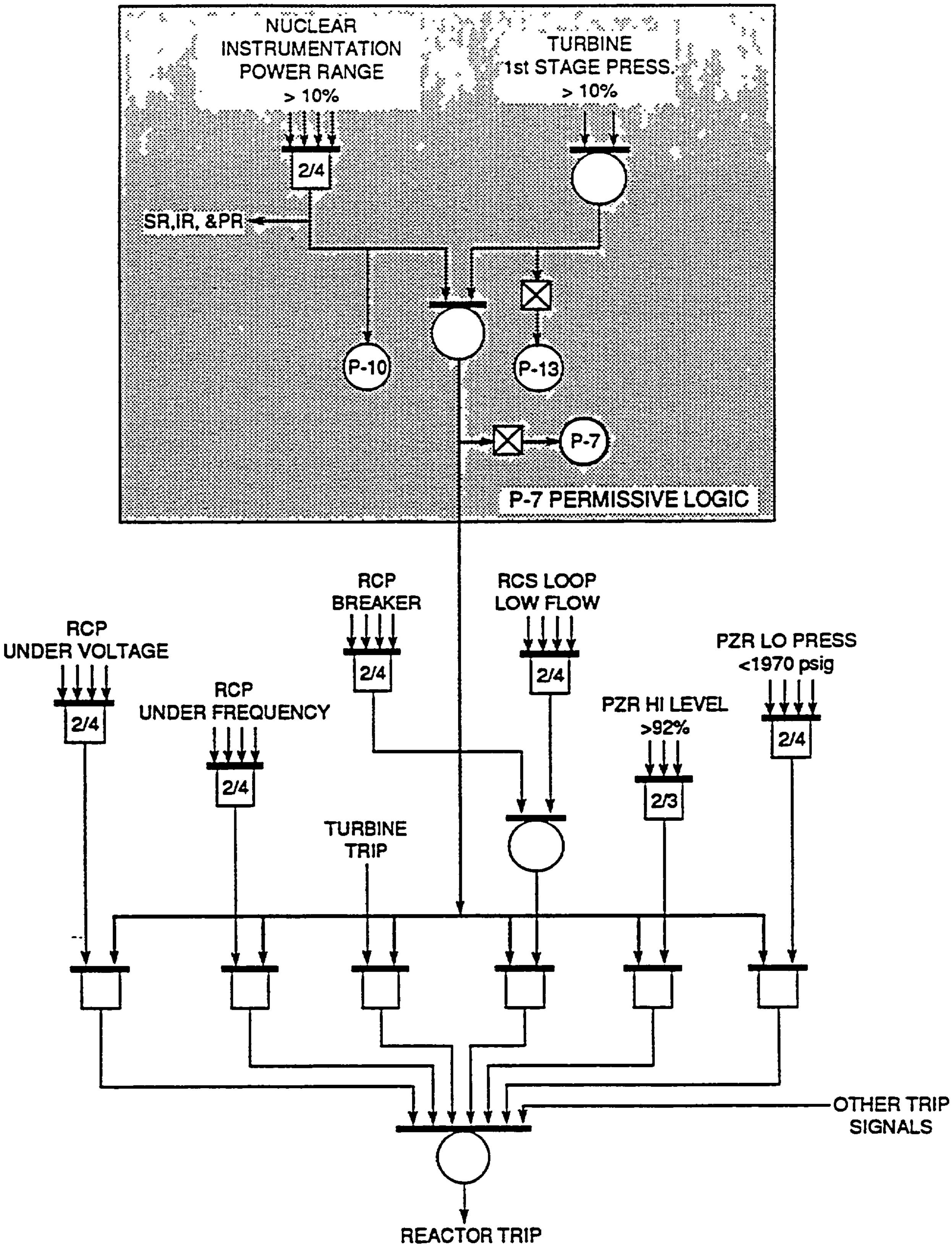


Figure 5-17. Training Sketch of Reactor Trip Logic

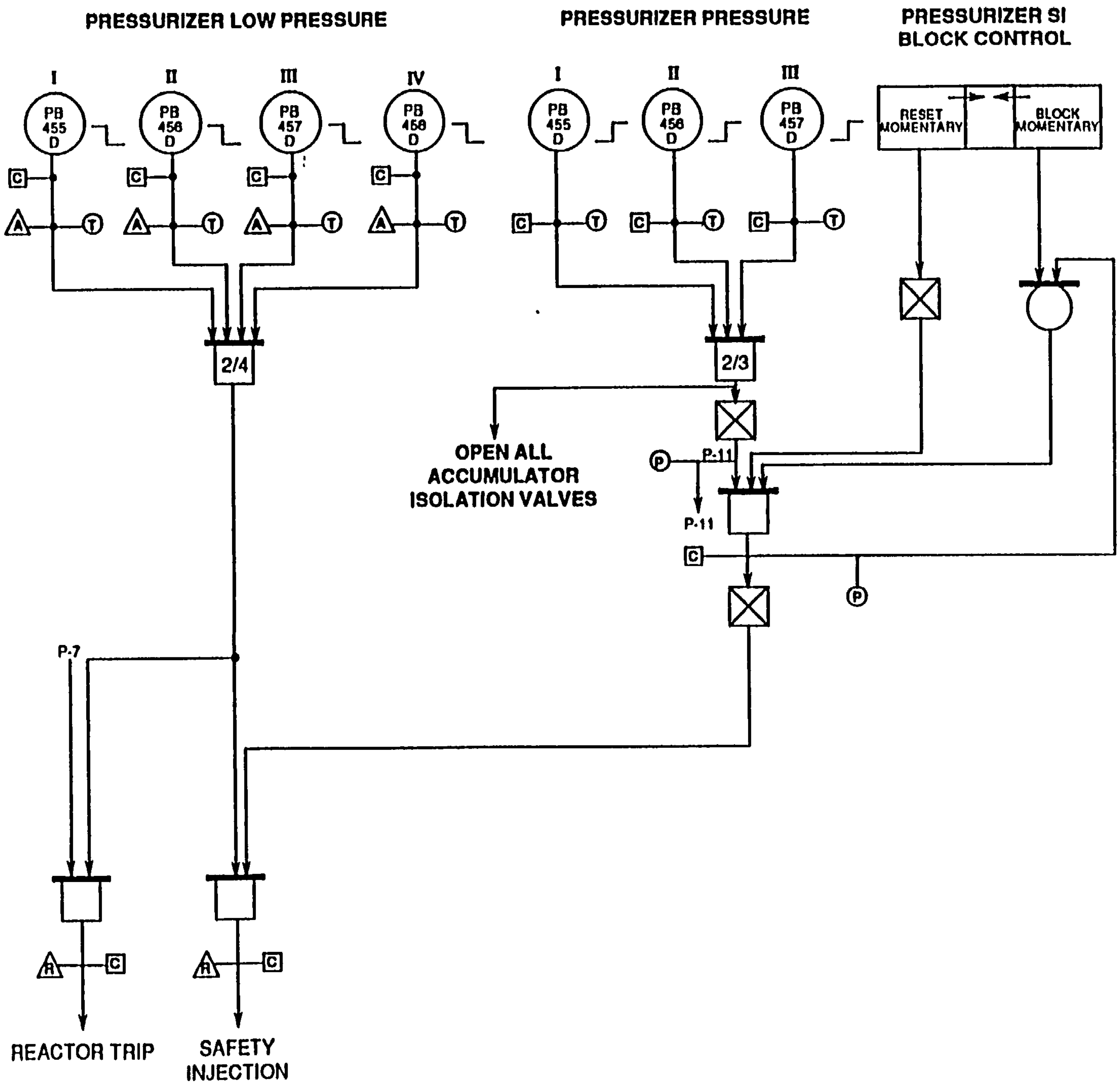


Figure 5-18. Pressurizer Pressure Logic Diagram

APPENDIX 5A. STANDARD ELECTRICAL DEVICE NUMBERS AND FUNCTIONS

5A.1 Purpose of Device Function Number

A device function number, with appropriate suffix letter or letters where necessary, is used to identify the function of each device in all types of partial automatic and automatic and in many types of manual switchgear. These numbers are to be used on drawings, on elementary and connection diagrams, in instruction books, in all publications, and in specifications.

Note: These device function designations, which have been developed as a result of usage over many years, may define the actual function the device performs in an equipment or they may refer to the electrical or other quantity to which the device is responsive. Hence, there may be in some instances a choice of the function number to be used for a given device. The preferable choice to be made in all cases should be the one that is recognized to have the narrowest interpretation so that it most specifically identifies the device in the minds of all individuals concerned with the design and operation of the equipment.

5A.2 Standard Device Function Numbers

Standard device function numbers, each with its corresponding function name and the general description of each function, are listed below:

Note: When alternate names and descriptions are included under the function, only the name and description which applies to each specific case should be used. In general, only one name for each device, such as "relay," "contactor," "circuit breaker," "switch," "monitor," or other "device" is included in each function designation. However, when the function is not inherently restricted to any specific type of device and where the type of device itself is merely incidental, any one of the above listed alternative names, as applicable, may be substituted. For example, if for device function 6 a contactor is used for the purpose in place of a circuit breaker, the function name should be specified as Starting Contactor.

Numbers from 95 to 99 should be assigned only for those functions in specific cases where none of the assigned standard device function numbers are applicable. Numbers that are "reserved for future application" should not be used.

1. **MASTER ELEMENT** is the initiating device, such as a control switch, voltage relay, float switch, etc., that serves either directly or through such permissive devices as protective and time-delay relays to place an equipment in or out of operation.

2. **TIME-DELAY STARTING OR CLOSING RELAY** is a device that functions to give a desired amount of time delay before or after any point of operation in a switching sequence or protective relay system, except as specifically provided by device functions 48, 62, and 79.

3. **CHECKING OR INTERLOCKING RELAY** is a relay that operates in response to the position of a number of other devices (or to a number of predetermined conditions) in an equipment, to allow an operating sequence to proceed, or to stop, or to provide a check of the position of these devices or of these conditions for any purpose.

4. **MASTER CONTACTOR** is a device, generally controlled by device function 1 or the equivalent and the required permissive and protective devices, that serves to make and break the necessary control circuits to place an equipment into operation under the desired conditions and to take it out of operation under other or abnormal conditions.

5. **STOPPING DEVICE** is a control device used primarily to shut down an equipment and hold it out of operation. This device may be manually or electrically actuated, but excludes the function of electrical lockout (see device function 86) on abnormal conditions.

6. **STARTING CIRCUIT BREAKER** is a device whose principal function is to connect a machine to its source of starting voltage.

7. **ANODE CIRCUIT BREAKER** is a device used in the anode circuits of a power rectifier for the primary purpose of interrupting the rectifier circuit if an arcback should occur.

8. **CONTROL POWER DISCONNECTING DEVICE** is a disconnecting device, such as a knife switch, circuit breaker, or pullout fuse block, used for the purpose of respectively connecting and disconnecting the source of control power to and from the control bus or equipment.

Note: Control power is considered to include auxiliary power which supplies such apparatus as small motors and heaters.

9. **REVERSING DEVICE** is a device that is used for the purpose of reversing a machine field or for performing any other reversing functions.

10. **UNIT SEQUENCE SWITCH** is a switch that is used to change the sequence in which units may be placed in and out of service in multiple-unit equipments.

11. Reserved for future application.

12. **OVERSPEED DEVICE** is usually a direct-connected speed switch which functions on machine overspeed.

13. **SYNCHRONOUS SPEED DEVICE** is a device such as a centrifugal speed switch, a slip frequency relay, a voltage relay, an undercurrent relay, or any type of device that operates at approximately the synchronous speed of a machine.

14. **UNDERSPEED DEVICE** is a device that functions when the speed of a machine falls below a predetermined value.

15. **SPEED OR FREQUENCY MATCHING DEVICE** is a device that functions to match and hold the speed or the frequency of a machine or of a system equal to, or approximately equal to, that of another machine, source, or system.

16. Reserved for future application.

17. **SHUNTING OR DISCHARGE SWITCH** is a switch that serves to open or to close a shunting circuit around any piece of apparatus (except a resistor), such as a machine field, a machine armature, a capacitor, or a reactor.

Note: This excludes devices that perform such shunting operations as may be necessary in the process of starting a machine by devices 6 or 42, or their equivalent, and also excludes function 73 that serves for the switching of resistors.

18. **ACCELERATING OR DECELERATING DEVICE** is a device that is used to close or to cause the closing of circuits which are used to increase or decrease the speed of a machine.

19. **STARTING-TO-RUNNING TRANSITION CONTACTOR** is a device that operates to initiate or cause the automatic transfer of a machine from the starting to the running power connection.

20. **VALVE** is one used in a vacuum, air, gas, oil, or similar line, when it is electrically operated or has electrical accessories such as auxiliary switches.

21. **DISTANCE RELAY** is a relay that functions when the circuit admittance, impedance, or reactance increases or decreases beyond predetermined limits.

22. **EQUALIZER CIRCUIT BREAKER** is a breaker that serves to control or to make and break the equalizer or the current-balancing connections for a machine field, or for regulating equipment, in a multiple-unit installation.

23. **TEMPERATURE CONTROL DEVICE** is a device that functions to raise or lower the temperature of a machine or other apparatus, or of any medium, when its temperature falls below, or rises above, a predetermined value.

Note: An example is a thermostat that switches on a space heater in a switchgear assembly when the temperature falls to a desired value as distinguished from a device that is used to provide automatic temperature regulation between close limits and would be designated as device function 90T.

24. Reserved for future application.

25. **SYNCHRONIZING OR SYNCHRONISM-CHECK DEVICE** is a device that operates when two alternating current circuits are within the desired limits of frequency, phase angle, or voltage, to permit or to cause paralleling of these two circuits.

26. **APPARATUS THERMAL DEVICE** is a device that functions when the temperature of the shunt field or the amortisseur winding of a machine, or that of a load limiting or load shifting resistor or of a liquid or other medium, exceeds a predetermined value; or if the temperature of the protected apparatus, such as a power rectifier, or of any medium decreases below a predetermined value.

27. **UNDERVOLTAGE RELAY** is a relay that functions on a given value of undervoltage.

28. **FLAME DETECTOR** is a device that monitors the presence of the pilot or main flame in such apparatus as a gas turbine or a steam boiler.

29. **ISOLATING CONTACTOR** is a device that is used expressly for disconnecting one circuit from another for the purposes of emergency operation, maintenance, or test.

30. **ANNUNCIATOR RELAY** is a nonautomatically reset device that gives a number of separate visual indications upon the functioning of protective devices, and which may also be arranged to perform a lockout function.

31. **SEPARATE EXCITATION DEVICE** is a device that connects a circuit, such as the shunt field of a synchronous converter, to a source of separate excitation during the starting sequence; or one that energizes the excitation and ignition circuits of a power rectifier.

32. **DIRECTIONAL POWER RELAY** is a device that functions on a desired value of power flow in a given direction or upon reverse power resulting from arcback in the anode or cathode circuits of a power rectifier.

33. **POSITION SWITCH** is a switch that makes or breaks contact when the main device or piece of apparatus, which has no device function number, reaches a given position.

34. **MASTER SEQUENCE DEVICE** is a device such as a motor-operated multicontact switch, or the equivalent, or a programming device, such as a computer, that establishes or determines the operating sequence of the major devices in an equipment during starting and stopping or during other sequential switching operations.

35. **BRUSH-OPERATING OR SLIPRING SHORT-CIRCUITING DEVICE** is a device for raising, lowering, or shifting the brushes of a machine, or for short-circuiting its sliprings, or for engaging or disengaging the contacts of a mechanical rectifier.

36. **POLARITY OR POLARIZING VOLTAGE DEVICE** is a device that operates, or permits the operation of, another device on a predetermined polarity only, or verifies the presence of a polarizing voltage in an equipment.

37. **UNDERCURRENT OR UNDER-POWER RELAY** is a relay that functions when the current or power flow decreases below a predetermined value.

38. **BEARING PROTECTIVE DEVICE** is a device that functions on excessive bearing temperature, or on other abnormal mechanical conditions associated with the bearing, such as undue wear, which may eventually result in excessive bearing temperature or failure.

39. **MECHANICAL CONDITION MONITOR** is a device that functions upon the occurrence of an abnormal mechanical condition (except that associated with bearings as covered under device function 38), such as excessive vibration, eccentricity, expansion, shock, tilting, or seal failure.

40. **FIELD RELAY** is a relay that functions on a given or abnormally low value or failure of machine field current, or on an excessive value of the reactive component of armature current in an AC machine indicating abnormally low field excitation.

41. **FIELD CIRCUIT BREAKER** is a device that functions to apply or remove the field excitation of a machine.

42. **RUNNING CIRCUIT BREAKER** is a device whose principal function is to connect a machine to its source of running or operating voltage. This function may also be used for a device, such as a contactor, that is used in series with a circuit breaker or other fault protecting means, primarily for frequent opening and closing of the circuit.

43. **MANUAL TRANSFER OR SELECTOR DEVICE** is a manually operated device that transfers the control circuits to modify the plan of operation of the switching equipment or of some of the devices.

44. **UNIT SEQUENCE STARTING RELAY** is a relay that functions to start the next available unit in a multiple-unit equipment upon the failure or nonavailability of the normally preceding unit.

45. **ATMOSPHERIC CONDITION MONITOR** is a device that functions upon the occurrence of an abnormal atmospheric condition, such as damaging fumes, explosive mixtures, smoke, or fire.

46. **REVERSE-PHASE OR PHASE-BALANCE CURRENT RELAY** is a relay that functions when the polyphase currents are of reverse-phase sequence, or when the polyphase currents are unbalanced or contain negative phase-sequence components above a given amount.

47. **PHASE-SEQUENCE VOLTAGE RELAY** is a relay that functions upon a predetermined value of polyphase voltage in the desired phase sequence.

48. **INCOMPLETE SEQUENCE RELAY** is a relay that generally returns the equipment to the normal or off position and locks it out if the normal starting, operating, or stopping sequence is not properly completed within a predetermined time. If the device is used for alarm purposes only, it should preferably be designated as 48A (alarm).

49. **MACHINE OR TRANSFORMER THERMAL RELAY** is a relay that functions when the temperature of a machine armature or other load-carrying winding or element of a machine or the temperature of a power rectifier or power transformer (including a power rectifier transformer) exceeds a predetermined value.

50. **INSTANTANEOUS OVERCURRENT OR RATE-OF-RISE RELAY** is a relay that functions instantaneously on an excessive value of current or on an excessive rate of current rise, thus indicating a fault in the apparatus or circuit being protected.

51. **AC TIME OVERCURRENT RELAY** is a relay with either a definite or inverse time characteristic that functions when the current in an AC circuit exceeds a predetermined value.

52. **AC CIRCUIT BREAKER** is a device that is used to close and interrupt an AC power circuit under normal conditions or to interrupt this circuit

under fault or emergency conditions.

53. **EXCITER OR DC GENERATOR RELAY** is a relay that forces the DC machine field excitation to build up during starting or which functions when the machine voltage has built up to a given value.

54. Reserved for future application.

55. **POWER FACTOR RELAY** is a relay that operates when the power factor in an AC circuit rises above or falls below a predetermined value.

56. **FIELD APPLICATION RELAY** is a relay that automatically controls the application of the field excitation to an AC motor at some predetermined point in the slip cycle.

57. **SHORT-CIRCUITING OR GROUNDING DEVICE** is a primary circuit switching device that functions to short-circuit or to ground a circuit in response to automatic or manual means.

58. **RECTIFICATION FAILURE RELAY** is a device that functions if one or more anodes of a power rectifier fail to fire, or to detect an arcback, or on failure of a diode to conduct or block properly.

59. **OVERVOLTAGE RELAY** is a relay that functions on a given value of overvoltage.

60. **VOLTAGE OR CURRENT BALANCE RELAY** is a relay that operates on a given difference in voltage, or current input or output, of two circuits.

61. **CURRENT BALANCE RELAY** is a device which actuates on a given difference in current input or output of two circuits.

62. **TIME-DELAY STOPPING OR OPENING RELAY** is a time-delay relay that serves in conjunction with the device that initiates the shutdown, stopping, or opening operation in an automatic sequence or protective relay system.

63. **LIQUID OR GAS PRESSURE OR VACUUM RELAY** is a relay that operates on given values of liquid or gas pressure or on given rates of change of these values.

64. **GROUND PROTECTIVE RELAY** is a relay that functions on failure of the insulation of a machine, transformer, or of other apparatus to ground, or on flashover of a DC machine to ground.

Note: This function is assigned only to a relay that detects the flow of current from the frame of a machine or enclosing case or structure of a piece of apparatus to ground, or detects a ground on a normally ungrounded winding or circuit. It is not applied to a device connected in the secondary circuit of a current transformer, or in the secondary neutral of current transformers, connected in the power.

65. **GOVERNOR** is the assembly of fluid, electrical, or mechanical control equipment used for regulating the flow of water, steam, or other medium to the prime mover for such purposes as starting, holding speed or load, or stopping.

66. **NOTCHING OR JOGGING DEVICE** is a device that functions to allow only a specified number of operations of a given device, or equipment, or a specified number of successive operations within a given time of each other. It is also a device that functions to energize a circuit periodically or for fractions of specified time intervals, or that is used to permit intermittent acceleration or jogging of a machine at low speeds for mechanical positioning.

67. **AC DIRECTIONAL OVERCURRENT RELAY** is a relay that functions on a desired value of AC overcurrent flowing in a predetermined directior.

68. **BLOCKING RELAY** is a relay that initiates a pilot signal for blocking of tripping on external faults in a transmission line or in other apparatus under predetermined conditions, or cooperates with other devices to block tripping or to block

reclosing on an out-of-step condition or on power swings.

69. **PERMISSIVE CONTROL DEVICE** is generally a two-position, manually operated switch that, in one position, permits the closing of a circuit breaker, or the placing of an equipment into operation, and in the other position prevents the circuit breaker or the equipment from being operated.

70. **RHEOSTAT** is a variable resistance device used in an electric circuit, which is electrically operated or has other electrical accessories, such as auxiliary, position, or limit switches.

71. **LIQUID OR GAS-LEVEL RELAY** is a relay that operates on given values of liquid or gas level or on given rates of change of these values.

72. **DC CIRCUIT BREAKER** is a circuit breaker that is used to close and interrupt a DC power circuit under normal conditions or to interrupt this circuit under fault or emergency conditions.

73. **LOAD-RESISTOR CONTACTOR** is a contactor that is used to shunt or insert a step of load limiting, shifting, or indicating resistance in a power circuit, or to switch a space heater in circuit, or to switch a light or regenerative load resistor of a power rectifier or other machine in and out of circuit.

74. **ALARM RELAY** is a relay other than an annunciator, as covered under device function 30, that is used to operate, or to operate in connection with, a visual or audible alarm.

75. **POSITION CHANGING MECHANISM** is a mechanism that is used for moving a main device from one position to another in an equipment; as for example, shifting a removable circuit breaker unit to and from the connected, disconnected, and test positions.

76. **DC OVERCURRENT RELAY** is a relay that functions when the current in a DC circuit exceeds a given value.

77. **PULSE TRANSMITTER** is used to generate and transmit pulses over a telemetering or pilot-wire circuit to the remote indicating or receiving device.

78. **PHASE ANGLE MEASURING OR OUT-OF-STEP PROTECTIVE RELAY** is a relay that functions at a predetermined phase angle between two voltages or between two currents or between voltage and current.

79. **AC RECLOSING RELAY** is a relay that controls the automatic reclosing and locking out of an AC circuit interrupter.

80. **LIQUID OR GAS FLOW RELAY** is a relay that operates on given values of liquid or gas flow or on given rates of change of these values.

81. **FREQUENCY RELAY** is a relay that functions on a predetermined value of frequency (either under or over or on normal system frequency) or rate of change of frequency.

82. **DC RECLOSING RELAY** is a relay that controls the automatic closing and reclosing of a DC circuit interrupter, generally in response to load circuit conditions.

83. **AUTOMATIC SELECTIVE CONTROL OR TRANSFER RELAY** is a relay that operates to select automatically between certain sources or conditions in an equipment, or performs a transfer operation automatically.

84. **OPERATING MECHANISM** is the complete electrical mechanism or servomechanism, including the operating motor, solenoids, position switches, etc., for a tap changer, induction regulator, or any similar piece of apparatus that otherwise has no device function number.

85. **CARRIER OR PILOT-WIRE RECEIVER RELAY** is a relay that is operated or restrained by a signal used in connection with carrier current or

DC pilot-wire fault directional relaying.

86. **LOCKING-OUT RELAY** is an electrically operated hand, or electrically, reset relay or device that functions to shut down or hold an equipment out of service, or both, upon the occurrence of abnormal conditions.

87. **DIFFERENTIAL PROTECTIVE RELAY** is a protective relay that functions on a percentage or phase angle or other quantitative difference of two currents or of some other electrical quantities.

88. **AUXILIARY MOTOR OR MOTOR GENERATOR** is one used for operating auxiliary equipment, such as pumps, blowers, exciters, rotating magnetic amplifiers, etc.

89. **LINE SWITCH** is a switch used as a disconnecting, load-interrupter, or isolating switch in an AC or DC power circuit, when this device is electrically operated or has electrical accessories, such as an auxiliary switch, magnetic lock, etc.

90. **REGULATING DEVICE** is a device that functions to regulate a quantity, or quantities, such as voltage, current, power, speed, frequency, temperature, and load, at a certain value or between certain (generally close) limits for machines, tie lines, or other apparatus.

91. **VOLTAGE DIRECTIONAL RELAY** is a relay that operates when the voltage across an open circuit breaker or contactor exceeds a given value in a given direction.

92. **VOLTAGE AND POWER DIRECTIONAL RELAY** is a relay that permits or causes the connection of two circuits when the voltage difference between them exceeds a given value in a predetermined direction and causes these two circuits to be disconnected from each other when the power flowing between them exceeds a given value in the opposite direction.

93. **FIELD CHANGING CONTACTOR** is a contactor that functions to increase or decrease, in one step, the value of field excitation on a machine.

94. **TRIPPING OR TRIP-FREE RELAY** is a relay that functions to trip a circuit breaker, contactor, or equipment, or to permit immediate tripping by other devices; or to prevent immediate reclosure of a circuit interrupter if it should open automatically even though its closing circuit is maintained closed.

95-99. Used only for specific applications in individual installations where none of the assigned numbered functions from 1 to 94 are suitable.

5A.3 Supervisory Control and Indication

A similar series of numbers, prefixed by the letters RE (for "remote") shall be used for the interposing relays performing functions that are controlled directly from the supervisory system. Typical examples of such device functions are: RE1, RE5, and RE94.

Note: The use of the "RE" prefix for this purpose in place of the former 200 series of numbers now makes it possible to obtain increased flexibility of the device function numbering system. For example, in pipeline pump stations, the numbers 1 through 99 are applied to device functions that are associated with the overall station operation. A similar series of numbers, starting with 101 instead of 1, are used for those device functions that are associated with unit 1; a similar series starting with 201, for device functions that are associated with unit 2; and so on, for each unit in these installations. For switchyard use the device function numbers derived from the switch numbers. The common equipment will use the same series as is used for the switch numbers and the equipment associated with each bay will be formulated by adding a zero to the series being used for the switch numbers.

5A.4 Suffix Letters

Suffix letters are listed and classified in the several general groupings from section 5A.4.1 through 5A.4.5 and may be used with device function numbers for various purposes. They permit a manifold multiplication of available function designations for the large number and variety of devices used in the many types of equipment covered by this standard. Suffix letters may also serve to denote individual or specific parts or auxiliary contacts of these devices or certain distinguishing features, characteristics, or conditions that describe the use of the device or its contacts in the equipment.

Letter suffixes should, however, be used only when they accomplish a useful purpose. For example, when all of the devices in an equipment are associated with only one kind of apparatus, such as a feeder or motor or generator, to retain maximum simplicity in device function identification, the respective suffix letter F or M or G should not be added to any of the device function numbers.

To prevent any possible conflict or confusion, each suffix should preferably have only one meaning in an individual equipment. To accomplish this, short distinctive abbreviations, such as contained in Drafting Standards Abbreviations, or any appropriate combination of letters, may also be used as letter suffixes, where necessary. However, each suffix should not consist of more than three (preferably not more than two) letters, in order to keep the complete function designation as short and simple as possible.

The meaning of each suffix used with a device function number should be designated in the following manner on the necessary drawings or publications applying to the equipment: TC, Trip Coil; V, Voltage; X, Auxiliary Relay.

In the cases where the same suffix (consisting of one letter or a combination of letters) has different meanings in the same equipment, depending upon the device function number with which it is used, then the complete device function number with its suffix letter or letters and its corresponding function name should be listed in the legend in each case, as follows: 63V, Vacuum Relay; 70R, Raising Relay for Device 70; 90V, Voltage Regulator.

5A.4.1 Letters for Separate Auxiliary Devices

These letters denote separate auxiliary devices, such as:

- C - Closing relay or contactor
- CL - Auxiliary relay, closed (energized when main device is in closed position)
- CS - Control switch
- D - "Down" position switch relay
- L - Lowering relay
- O - Opening relay or contactor
- OP - Auxiliary relay, open (energized when main device is in open position)
- PB - Pushbutton
- R - Raising relay
- U - "Up" position switch relay
- X, Y, Z - Auxiliary relays

Note: In the control of a circuit breaker with an X-Y control scheme, the X relay is the device whose main contacts are used to energize the closing coil or the device which in some other manner, such as by the release of stored energy, causes the breaker to close. The contacts of the Y relay provide the antipump feature for the circuit breaker.

5A.4.2 Letters for Condition/Electrical Quantity

These letters indicate the condition or electrical quantity to which the device responds, or the medium in which it is located, such as:

- A - Air or amperes
- C - Current
- E - Electrolyte
- F - Frequency or flow or fault
- L - Level or liquid
- P - Power or pressure

PF - Power factor
Q - Oil
S - Speed
T - Temperature
V - Voltage or volts or vacuum
VAR - Reactive power
VB - Vibration
W - Water or watts

5A.4.3 Letters for Location of Main Device in the Circuit

These letters denote the location of the main device in the circuit, or the type of circuit in which the device is used, or the type of circuit or apparatus with which it is associated, when this is necessary, such as:

A - Alarm or auxiliary power
AC - Alternating current
AN - Anode
B - Battery or blower or bus
BK - Brake
BP - Bypass
BT - Bus tie
C - Capacitor or condenser or compensator or carrier current
CA - Cathode
D - Discharge
DC - Direct Current
E - Exciter
F - Feeder or field or filament
G - Generator or ground*
H - Heater or housing
L - Line or logic
M - Motor or metering
N - Network or neutral*
P - Pump or phase comparison
R - Reactor or rectifier
S - Synchronizing or secondary
T - Transformer or thyratron
TH - Transformer (high-voltage side)
TL - Transformer (low-voltage side)
TM - Telemeter
U - Unit

*Suffix "N" is generally used in preference to "G" for devices connected in the secondary neutral of current transformers or in the secondary of a current transformer whose primary winding is located in the neutral of a machine or power transformer. In the case of transmission line relaying, the suffix "G" is more commonly used for those relays that operate on ground faults.

5A.4.4 Letters for Parts of the Main Device

These letters denote parts of the main device that are divided into the following categories:

1. All parts, such as the following, except auxiliary contacts, position switches, limit switches, and torque limit switches.

BK - Brake
C - Coil or condenser or capacitor
CC - Closing coil
HC - Holding coil
M - Operating motor
MF - Fly-ball motor
ML - Load-limit motor
MS - Speed adjusting or synchronizing motor
S - Solenoid
SI - Seal-in
TC - Trip coil
V - Valve

2. All auxiliary contacts and position and limit switches for such devices and equipment as circuit breakers, contactors, valves and rheostats, and contacts of relays.

An "a" contact is open when the main device is in the standard reference position, commonly referred to as the nonoperated or deenergized position, and closes when the device assumes the opposite position.

A "b" contact is closed when the main device is in the standard reference position, commonly referred to as the nonoperated or deenergized position, and opens when the device assumes the opposite position.

Standard reference position of some typical devices are as follows:

Device	Standard Reference Position
Power Circuit Breaker	Main Contacts Open
Disconnecting Switch	Main Contacts Open
Load-break Switch	Main Contacts Open
Valve	Closed Position
Gate	Closed Position
Clutch	Disengaged Position
Turning Gear	Disengaged Position
Power Electrodes	Maximum Gap Position
Rheostat	Maximum Resistance Position
Adjusting Means**	Low or Down Position
Relay+	Deenergized Position
Contactor+	Deenergized Position
Relay (latched-in type)	See 5A.7
Contactor (latched-in type)	Main Contacts Open
Temperature Relay#	Lowest Temperature
Level Detector#	Lowest Level
Flow Detector#	Lowest Flow
Speed Switch	Lowest Speed
Vibration Detector#	Minimum Vibration
Pressure Switch#	Lowest Pressure
Vacuum Switch#	Lowest Pressure (Highest Vacuum)

**These may be speed, voltage, current, load, or similar adjusting devices comprising rheostat, springs, levers, or other components for the purpose.

+These electrically operated devices are of the nonlatched-in type, whose contact position is dependent only upon the degree of energization of the operating or restraining or holding coil or coils that may or may not be suitable for continuous energization. The deenergized position of the device is that with all coils deenergized.

#The energizing influences for these devices are considered to be, respectively, rising temperature, rising level, increasing flow, rising speed, increasing vibration, and increasing pressure.

The simple designation "a" or "b" is used in all cases where there is no need to adjust the contacts to change position at any particular point in the travel of the main device or where the part of the travel where the contacts change position is of no significance in the control or operating scheme. Hence the "a" and "b" designations usually are sufficient for circuit breaker auxiliary switches.

5A.4.4.1 Auxiliary Switches with Defined Operating Positions

When it is desired to have the auxiliary, position, or limit switch designation indicate at what point of travel the contacts change position, as is sometimes necessary in the case of valves and for other main devices, then an additional letter (or a percentage figure, if required) is added (as a suffix to the "a" and "b" designation) for the purpose.

For a valve, the method of designating such position switches is shown in the diagram and legend designated "valve position." There are two points to consider in visualizing or describing the operation of these position switches. The first is whether another contact is an "a" or "b" as indicated by the first letter. The second is where the contact changes position, either at or near:

- The closed position of the valve (c)
- The open position of the valve (o), or
- A specified percentage, such as 25% of the full open position.

When applied to devices other than valves, gates, circuit breakers, and switches for which the letters "o" and "c" are used for "open" and "closed," respectively, it will be necessary to use other applicable letters. For example, for such devices as a clutch, turning gear, rheostat, electrode, and adjusting device, the letters "d," "e," "h," "1," "u," and "d" meaning "disengaged," "engaged," "high," "low," "up," and "down," respectively, are applicable. Also, other appropriate suffix letters may be used for special "a" or "b" position switches, when these are considered more appropriate and if their meaning is clearly indicated. For example, in the case of an early opening auxiliary switch on a power circuit breaker, adjusted to open when the breaker is tripped before the main contacts part, it may be thus described and then designated as an "ac" auxiliary switch.

Eight possible valve positions can be described as follows:

ac - "a" contact that changes position at or near the closed position of the valve (i.e., open only when valve is fully closed).

ao - "a" contact that changes position at or near the open position of the valve (i.e., closed only when valve is fully open).

bc - "b" contact that changes position at or near the closed position of the valve (i.e., closed only when valve is fully closed).

bo - "b" contact that changes position at or near the open position of the valve (i.e., open only when valve is fully open).

a25 - "a" contact that changes position when valve is 25% open (i.e., closed only when valve is open 25% or more).

a75 - "a" contact that changes position when valve is 75% open (i.e., closed only when valve is open 75% or more).

b25 - "b" contact that changes position when valve is 25% open (i.e., closed only when valve is open less than 25%).

b75 - "b" contact that changes position when valve is 75% open (i.e., closed only when valve is open less than 75%).

5A.4.4.2 Auxiliary Switches for Circuit Breaker Operating Mechanisms

For the mechanically tripfree mechanism of a circuit breaker the following designations are used:

"a" - Contact that is open when the operating mechanism of the main device is in the nonoperated position and that closes when the operating mechanism assumes the opposite position.

"b" - Contact that is closed when the operating mechanism of the main device is in the nonoperated position and that opens when the operating mechanism assumes the opposite position.

The part of the stroke at which the auxiliary switch changes position should, if necessary, be specified in the description. "LC" is used to designate the latch-checking switch of such a mechanism, which is closed when the mechanism linkage is relatched after an opening operation of the circuit breaker.

5A.4.4.3 Limit Switches

"LS" designates a limit switch. This is a position switch that is actuated by a main device, such as a rheostat or valve, at or near its extreme end of travel. Its usual function is to open the circuit of the operating motor at the end of travel of the main device, but it may also serve to give an indication that the main device has reached an extreme position of travel. The designations "ac," "ao," "bc," and "bo," as illustrated above, are actually more descriptive for valve limit switches than such designations as "LSC" or "LSO." Also, in the case of a fuel transfer device, designations such as a100G, b100G, a100L, and b100L are more descriptive than "LS" designations. In both cases they indicate whether the specific contact is an "a" or a "b."

5A.4.4.4 Torque Limit Switches

This is a switch that is used to open an operating motor circuit at a desired torque limit at the extreme end of travel of a main device, such as a valve. This switch should be designated as follows:

tqc - Torque limit switch, opened by torque - responsive mechanism, to stop valve closing.
tqo - Torque limit switch, opened by torque-responsive mechanism, to stop valve opening.

5A.4.4.5 Other Devices

If several similar auxiliary, position, and limit switches are present on the same main device, they should be designated with supplementary numerical suffixes as 1, 2, 3, etc., when necessary.

5A.4.5 Other Letter Designations

The following letters cover all other distinguishing characteristics or conditions that serve to describe the use of the device or its contacts in the equipment.

A	-	Accelerating or automatic
B	-	Blocking or backup
C	-	Close or cold
D	-	Decelerating or detonate or down or disengaged.
E	-	Emergency or engaged
F	-	Failure of forward
H	-	Hot or high
HR	-	Hand reset
HS	-	High speed
L	-	Left or local or low or lower or leading
M	-	Manual
O	-	Open
OFF	-	Off
ON	-	On
P	-	Polarizing
R	-	Right or raise or reclosing or receiving or remote or reverse
S	-	Sending or swing
T	-	Test or trip or trailing
TDC	-	Time-delay closing
TDO	-	Time-delay opening
U	-	Up

5A.4.6 Lower Case Letters

Lowercase (small) suffix letters are used in practically all instances on electrical diagrams for auxiliary, position, and limit switches. Capital letters are generally used for all other suffix letters.

The letters in 5A.4.1 to 5A.4.3 should generally form part of the device function designation and are usually written directly after the device function number, (e.g., 52CS, 70W, or 49D). When it is necessary to use two types of suffix letters in connection with one function number, it is often desirable for clarity to separate them by a slanted line or dash, as (e.g., 20D/CS or 20D-CS).

The suffix letters in 5A.4.4, which denote parts of the main device, and those in 5A.4.5, which cannot or need not form part of the device function designation, are generally written directly below the device function number on drawings, (e.g., $\underset{CC}{\underline{52}}$ or $\underset{A}{\underline{43}}$).

5A.5 <u>Suffix Numbers</u>

If two or more devices with the same function number and suffix letter (if used) are present in the same equipment, they may be distinguished by numbered suffixes, as for example, 4X-1, 4X-2, and 4X-3, when necessary.

5A.6 <u>Devices Performing More Than One Function</u>

If one device performs two relatively important functions in an equipment so that it is desirable to identify both of these functions, a double function number and name, such as 50/51 Instantaneous and Time Overcurrent Relay, may be used.

5A.7 Representation of Device Contacts on Electrical Diagrams

On electrical diagrams the "b" contacts of all devices, including those of relays and those with suffix letters or percentage figures, should be shown as closed contacts, and all "a" contacts should be shown as open contacts. The use of the single letters "a" and "b" with the contact representation is generally superfluous on the diagrams. However, these letters are a convenient means of reference in the test of instruction books, articles, and other publications.

The opening or closing settings of the contacts and auxiliary, position, and limit switches should (when necessary for the ready understanding of the operation of the devices in the equipment) be indicated on the elementary diagram for each such contact. In the case of relay contacts, this indication would consist of the numerical settings; and in the case of the switches, would consist of a chart similar to that illustrated in section 5A.4.4.1.

For those devices that have no deenergized or nonoperated position, such as manually operated transfer or control switches (including those of the spring-return type) or auxiliary position indicating contacts on the housings or enclosures of a removable circuit breaker unit, the preferred method of representing these contacts is as an "a" switch. Each contact should, however, be identified on the elementary diagram as to when it closes. For example, the contacts of the Manual-Automatic Transfer Switch, device function 43, which are closed in the automatic position, would be identified with the letter "A," and those that are closed in the manual position would be identified with the letter "M." The auxiliary position switches on the housing 52H of a removable circuit breaker unit, which are closed when the unit is in the connected position, may be identified by the suffix letters "IN," and those which are closed when the unit is withdrawn from the housing may be identified by the suffix letters "OUT."

In the case of latched-in or hand-reset locking-out relays, which operate from protective devices to perform the shutdown of an equipment and to hold it out of service, the contacts should preferably be shown in the normal nonlocking-out position. In general, any devices, such as electrically operated latched-in relays, which have no deenergized or nonoperated position, and have not been specifically covered in the above paragraphs should have their contacts shown in the position most suitable for the ready understanding of the operation of the devices in the equipment, and sufficient description should be present, as necessary, on the elementary diagram to indicate the contact operation.

6.0 BASIC ELECTRICAL

Learning Objectives

After studying this chapter, you should be able to:

1. State Ohm's Law and describe the behavior of resistors in series and parallel.
2. Explain the concept of electrical ground.
3. State the conditions necessary for a voltage to be induced in a conductor.
4. Explain the significance of the root mean square (rms) value of an alternating voltage or current.
5. Define the following properties of electrical circuits:
   a. Resistance
   b. Inductance
   c. Inductive reactance
   d. Capacitance
   e. Capacitive reactance
6. Define the following terms and state the unit of measurement for each:
   a. Real power
   b. Reactive power
   c. Apparent power
7. Describe the operation of a transformer.
8. Describe the operation of a relay.
9. Define power factor and describe the load characteristics associated with leading and lagging power factors.
10. Describe the relationship between line and phase voltages and currents in wye and delta connected circuits.
11. Explain why 3-phase AC power is preferred over single-phase AC power.
12. State and describe the terms of the equations for DC power, single-phase AC power, and 3-phase AC power.

6.1 Electrical Fundamentals

The study of electricity is fundamentally about the movement and behavior of electric charges. Each atom contains protons and electrons that carry positive and negative charges. The majority of charge movement is a result of the migration of negatively charged electrons.

Conductors are materials through which electric charges move most easily. Conductor atoms typically have at least one electron that is not closely held and can break free to create a moving charge. Examples of good conductors include metals such as copper, silver, gold, and aluminum.

Insulators, on the other hand, do not readily give up electrons and are poor conductors of electricity. Insulators are used as the "pipes" in electrical circuits to contain the charge movements along desired paths. Examples of good insulators are glass, mica, and rubber.

Semiconductors are substances like germanium and silicon that are neither good conductors nor good insulators. Semiconductors are used to make circuit devices like transistors and diodes.

An electric circuit is a network of conductors together with the components used to provide and remove or store energy from electric charges.

6.1.1 Voltage

Voltage (e) represents the work that must be done to move an electric charge from one position to the next and can be mathematically expressed by $e = \frac{dw}{dq}$ where q is the symbol for electrical charge and w is the symbol for work. Voltage is also referred to as electromotive force (emf) or potential difference. If one joule of energy must be expended to move a positive charge from point A to point B, the voltage of point B is one volt (v) higher (more positive) than the voltage at point A.

Voltage refers to a difference in potential and must be specified with respect to some reference. The circuit reference against which voltages are measured is called ground. In a true earth-grounded circuit, there is an electrical connection to the earth and all voltages are measured against the earth's potential. Typical house circuits are earth-grounded and have voltages of about 115 volts with respect to the potential of the earth. Some transmission lines have voltages of 345,000 volts above the earth's potential.

It is convenient to think of voltage as the force available to move charges. A battery, for example, has a potential difference (voltage) across its terminals that can be applied to charges to move them through a conductor.

6.1.2 Current

Current (i) is the rate of movement of electric charges through a conductor and can be mathematically expressed by $i = \frac{dq}{dt}$. The unit of current is the ampere (amp or a). One ampere exists when the charge flows at the rate of one coulomb per second, where one coulomb equals the charge of about 6.3×10^{18} electrons.

By convention, current flow is defined in this course as the flow of positive charges, which is opposite to the direction of flow of electrons.

Circuits in which the current flows in only one direction for the period under consideration are referred to as direct current (DC) circuits. Circuits in which the charges flow first in one direction and then the other, repeating the cycle with definite frequency, are known as alternating current (AC) circuits. Figure 6-1 illustrates this variation of current magnitude and direction in a typical AC circuit. Note that the convention used to represent a voltage rise or drop with an arrow has the arrow point at the higher potential. Note also that frequency is measured in hertz (Hz) where one Hz equals one cycle per second.

6.1.3 Resistance

Resistance is a measure of the opposition that charges encounter when moving through a material (i.e., opposition to current flow). The resistance of a material is measured in ohms (Ω) and Ohm's Law expresses the relationship between voltage, current, and resistance:

$$e = iR$$

where

e = voltage across a resistor (volts),
i = current through the resistor (amps), and
R = the resistance measured in ohms.

A 1 ohm resistor with 1 amp of current through it will have a voltage of 1 volt across it.

Resistors, like any circuit elements, can be connected in series or in parallel. Resistors in series each have the same current going through them, as shown in Figure 6-2A. When resistors are in series, the total resistance can be expressed as follows:

$$R_T = R_1 + R_2 + R_3 + \ldots$$

where

R_T = The total or equivalent resistance

R_1 = Resistor 1,

R_2 = Resistor 2, etc.

Resistors can also be connected in parallel as shown in Figure 6-2B. These resistors each have the same voltage drop across them and the total resistance can be found by:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$

where again

R_T = The total or equivalent resistance.

6.2 Electricity and Magnetism

A magnetic field is the region in the vicinity of a magnet in which forces exist that act on ferromagnetic material. Magnets are either artificial or natural, with each having two poles — one north and one south. The direction of the magnetic field outside a magnet is from the north pole to the south pole. This is illustrated in Figure 6-3. Due to the weak magnetic properties of natural magnets, artificial magnets are constructed to fit most applications.

Certain materials, called ferromagnetic materials, are more receptive to magnetic flux than is air or free space. These materials, notably iron and its alloys, can be used in devices to concentrate and confine the magnetic flux in much the same manner as conductors channel electric current.

Magnetic circuits may be constructed that are analagous in many ways to electric circuits. As stated above, ferromagnetic materials act as conductors of the magnetic flux that can be thought of as current. Magnetomotive force (MMF), similar to electromotive force, is the *magnetic* potential difference that tends to force flux through the magnetic circuit.

The opposition of the iron material to carrying flux is called reluctance and is analogous to electrical resistance. Reluctance is directly proportional to length, inversely proportional to cross-sectional area, and dependent on the material's magnetic receptiveness called its permeability.

6.2.1 Electric Current Produces a Magnetic Field

Electricity and magnetism are closely interrelated. A current carrying conductor (moving charges) will produce a magnetic field around the conductor. Artificial magnets, or electromagnets, take advantage of this fact. The MMF that results from a coil of wire through which current flows is given by:

$$MMF = N\,i \text{ ampere-turns},$$

where

MMF = magnetomotive force,
N = the number of turns of wire in the coil, and
i = the magnitude of the current through the wire.

Unlike the relationship between voltage and current through a resistance, the relationship between MMF and the resulting magnetic flux through a ferromagnetic material is non-linear. As more and more MMF is applied to a material, the resulting increase in flux becomes smaller and smaller until there is no increase in flux for increased MMF.

6.2.2 Simple Relay

The simple relay mechanism shown in Figure 6-4 is an application of the property of a current carrying conductor creating a magnetic field. The relay permits a weak current in one circuit (primary circuit) to control a heavy current flow in another circuit (secondary circuit). Therefore, a relay is a special switch that permits closing a circuit at some remote location. Relays are used in many control applications where normal switches are not practical. In Figure 6-4, when the switch is closed in the primary circuit, current flows from the battery through the coil of the electromagnet, setting up a magnetic field that attracts the flat blade of magnetic material called the armature. The armature pivots to close the contacts in the secondary circuit. Current then flows through the secondary circuit, consisting of a voltage source and load attached between terminals A and B. If the switch of the primary circuit is opened, the spring returns the armature to its original position, opening the contacts of the secondary circuit.

6.2.3 Electromagnetic Induction

A second phenomenon linking electricity and magnetism is electromagnetic induction. When there is relative motion between an electric conductor and a magnetic field (the lines of flux are "cut" by the conductor), a voltage is induced in the conductor. The relative motion in this case may be generated in several ways. The magnetic field may be stationary and the conductor moved across it. The conductor may be kept stationary and the magnetic field moved across it. Or finally, the conductor may be maintained stationary and the magnetic field built up and then collapsed in the vicinity of the conductor in such a way that the magnetic lines of flux "cut" the conductor. Electromagnetic induction of voltage is basic to the operation of transformers, motors, and generators.

6.2.4 Two Pole AC Generator

The two pole AC generator shown in Figure 6-5 is an example of a simple machine based on electromagnetic induction. The magnetic lines of flux go from left to right between the two magnetic poles and are symbolized by B. The conductor must be mechanically rotated and is physically attached to two slip rings that rotate with the wire loop. Brushes are normally made from carbon, which is a good conductor. The brushes are stationary and ride along the outside of the slip rings to provide a path for current flow between the stationary load resistor and the wire loop.

In Figure 6-6, sketch A, conductors 1 and 2 are moving parallel to the lines of flux at that instant. No lines of flux are being "cut" by the conductors and no voltage is induced. No current flows through the resistor.

In sketch B, part 1 of the conductor is beginning to move down in front of the south magnetic pole, and part 2 is beginning to move up in front of the north pole. There is relative motion now between the conductors and the magnetic field: therefore, voltage is induced in the conductors. The polarity of the induced voltage can be determined from the right hand rule. If the fingers of your right hand point in the direction of motion of the conductor and your fingers are curled toward the direction of the magnetic field, then your thumb will point in the direction of positive voltage induced in the conductor. In this case, positive voltage is induced toward the near side of part 1 and the far side of part 2 of the wire loop. The resulting current flows as shown by the arrow.

In sketch C, the relative motion between the conductor and the magnetic field is a maximum and the resulting induced voltage is a maximum. In general, the magnitude of the induced voltage is proportional to both the strength of the magnetic field and the amount of relative motion between the conductor and magnetic field.

In sketches F, G, and H of Figure 6-6, note that the direction of the induced voltage changes once the loop has rotated 180 degrees.

6.3 Real, Apparent and Reactive Power

Power is the rate of doing work or otherwise delivering energy. In electrical engineering, power is sometimes referred to as real power to distinguish it from terms taught later in this section. Real power is measured in watts (W) where one watt equals one joule per second. A 100 watt lamp, for example, is consuming 100 joules per second of energy.

From the definitions of voltage and current, the formula for instantaneous power consumed or provided by any element of a circuit can be derived as follows:

$$P = \frac{dw}{dt} = \frac{dw}{dq} \times \frac{dq}{dt}$$

recall $e = \frac{dw}{dq}$

and $i = \frac{dq}{dt}$

therefore, $P = ei$

where

p = instantaneous power (watts),
e = instantaneous voltage across the element (volts), and
i = instantaneous current through the element (amps).

In a DC circuit, voltage and current generally do not vary with time and the equation above can be expressed as:

$P = EI$

where

P = real power (watts)
E = steady-state DC voltage across the element, and
I = steady-state DC current through the element.

6.3.1 Root Mean Square or Effective Values of Voltage and Current

Though an AC sine wave makes a pretty picture, its continuous oscillations make it somewhat difficult to determine exactly a particular value of the voltage or current that can be said to be effective in an AC circuit. Just which of the many possible instantaneous values of voltage or current would or should an electric meter read? To settle this question we define the effective value of alternating current as that which would perform work at exactly the same rate as an equal value of direct current. This is precisely what has been done and the only question is, just what is this effective value of an AC current or voltage?

The easiest way to compare the rates of work (power) of an alternating current and a direct current is to measure the relative heating effect, when each flows through the same value of resistance. Accordingly, we define the effective value of an alternating current as that AC value which produces heat at exactly the same rate as an equal amount of direct current flowing through the same resistance. In other words, an effective value of 1 ampere AC will produce the same heat in a given resistor and given time as 1 ampere DC.

With this definition it is easy to compute the effective value of an alternating current. Heat production is proportional to the square of the current for a given resistance (heating rate = power = i^2R). So, let us square all the instantaneous values of an AC sine wave, as illustrated in Figure 6-7. The top graph shows a typical AC sine wave of the instantaneous current (i) against time, varying between peak values of $\pm I_m$. The bottom graph of Figure 6-7 illustrates the squared sine wave obtained when all the instantaneous values of the current (i) in the upper graph are squared and the corresponding i^2 values are then plotted against time. Note that the lower graph, because of the squaring process, has only positive values that oscillate between zero and I_m^2 about a new axis. Since the curve varies uniformly between these extreme values (0 and I_m^2), its average or mean value must be equal to $I_m^2/2$. We now need only extract the root of this mean-squared value ($1/2I_m^2$) to obtain the effective AC value in accordance with our definition. This value is frequently called the root-mean-square or rms value. Thus, the effective, or rms value (I) is

$$\sqrt{\frac{I_m^2}{2}} = \frac{I_m}{\sqrt{2}} = \frac{I_m}{1.414} = 0.707 I_m$$

Hence, for an AC current:

effective (rms) current value = $I = .707\ I_m$;

and, similarly, for an AC voltage:

effective (rms) voltage value = E = .707 E_m.

6.3.2 Real Power and Reactive Power in AC Circuits

There are three basic types of circuit elements that have been defined based on the relationship between voltage and current through them. These three elements are resistors, inductors, and capacitors. Each will be examined as to its behavior in an AC circuit.

6.3.2.1 Purely Resistive Circuits

In resistors, the relation between voltage across the resistor and current through the resistor is provided by Ohm's Law. The constant of proportionality is simply the resistance and is expressed by the following formula:

$$e = iR$$

where

- e = instantaneous voltage across the resistor (volts),
- i = instantaneous current through the resistor (amps), and
- R = resistance of the resistor (ohms).

Note that in a purely resistive circuit such as that shown in Figure 6-8, the voltage and current are in phase. That is, the sinusoidal voltage peaks at the same time as the current peaks. This relationship is predictable since the voltage and current are related by the resistance (R) which is a constant. In a *purely resistive circuit,* the power supplied by the source can be expressed by:

$$P = EI,$$

where

- P = real power (watts),
- E = source voltage (volts), and
- I = source current (amps).

6.3.2.2 Purely Inductive Circuits

Inductors are circuit elements in which the voltage is proportional to the time derivative or the rate of change of the current through it. Expressed mathematically, the voltage is

$$e = L\frac{di}{dt},$$

where

- L = the constant of proportionality called the <u>inductance</u> and is measured in *henrys* and
- $\frac{di}{dt}$ = rate of change of current through the conductor.

A simple inductor may be constructed by winding a coil of wire around a paper cylinder, and in fact all coils of conducting material have properties of inductance. The voltage-current relationship across an inductor is based upon the two principles discussed in sections 6.2.1 and 6.2.3 on electricity and magnetism.

When current is applied through the coils of the inductor, the current creates a magnetic field around and through the core of the inductor. If the applied current is changing (that is increasing and decreasing in magnitude and changing direction as with an AC current), then the magnetic field will also be building up and then collapsing, then building up in the opposite direction and collapsing again.

Applying the principle of electromagnetic induction, this changing magnetic field induces a voltage in the conductors of the coil (inductor). In this case, the coil is stationary and the magnetic field is "moving." The greater the rate of change of the magnetic field, the more lines of flux will be "cut" by the conductor, and the greater the voltage induced. This leads us back to the voltage-current relationship across an inductor that says that the voltage is proportional to the time derivative or the rate of change of current through the inductor.

Figure 6-9 illustrates the relationship between instantaneous voltage, current and power in a purely inductive circuit. Note that when the rate of change of current is maximum (as the current passes through zero), the voltage is at its peak. And when the rate of change of the current is zero (at its peak), the voltage is zero. Note also that while the voltage and current have the same frequency they are offset in phase by 90 degrees. For example, the voltage peaks at the 90 degree mark and the current peaks at the 180 degree mark. In other words, *current lags the voltage* by 90 degrees. This relationship is characteristic of all purely inductive circuits.

Figure 6-9 shows that the average power consumed in this circuit is zero. (This ignores the very real resistance of the conductors that make up the wires and the inductor.) In fact, the inductor acts as a source of power during one quarter cycle and a consumer of power in the next quarter cycle. What is happening in the inductor is that energy is alternately being stored in the magnetic field of the inductor and then returned back to the circuit as induced voltage.

Although the average gain or loss is zero, energy is clearly being transferred back and forth between the inductor and the circuit. This energy transfer is important from a practical viewpoint because it involves current that can be measured and for which conductors must be sized. The term used to describe this transfer of energy is reactive power (Q). Reactive power has units of volt-amps reactive (VAR) and in a *purely inductive circuit*, the reactive power can by calculated by

$$Q = EI,$$

where

Q = reactive power (VAR),
E = source voltage (volts), and
I = source current (amps).

It is important to remember that circuits do not have to contain inductors to have inductive properties. Any circuit in which current flows through coiled conductors exhibits inductive properties as described above.

6.3.2.3 Inductive Reactance

In an inductive AC circuit, the current is continually changing and is continuously inducing an emf. Because this emf opposes the continuous change in the flowing current, its effect is measured in ohms. This opposition of the inductance to the flow of an alternating current is called "inductive reactance" (X_L). The current flowing in a circuit which contains only inductive reactance is:

$$I = \frac{E}{X_L}$$

where

I = effective current (A)
X_L = inductive reactance (Ω), and
E = effective voltage across the reactance.

The value of X_L in any circuit is dependent on the inductance and the rate at which the current is changing. The rate of change depends on the frequency of the applied voltage. Therefore, X_L can be calculated as follows:

$$X_L = 2\pi fL,$$

where

π = 3.14,
f = frequency (Hz), and
L = inductance (H).

6.3.2.4 Purely Capacitive Circuits

Purely capacitive circuits are analogous in many ways to inductive circuits. Capacitors are circuit elements through which the current is proportional to the time derivative or the rate of change of the voltage across it (just the opposite of inductors). Expressed mathematically, the current is:

$$i = C \frac{de}{dt},$$

where

C = the constant of proportionality called the <u>capacitance</u> and is measured in *farads* and

$\frac{de}{dt}$ = rate of change of voltage across the capacitor.

A simple capacitor may be constructed by placing two conducting plates next to each other and separated by an insulator (paper or air) called a dielectric. A parallel plate capacitor of this type is illustrated in Figure 6-10 and can be used to describe the voltage current relationship in a capacitor.

When the switch is shut, positive charge builds up on one side of the capacitor and negative charge on the other. At the same time, current "through" the capacitor is immediately at maximum when the switch i shut and charge rapidly builds up on the two plates. As the voltage builds up and the potential difference between the battery and the capacitor decreases, the current decreases until in steady state the voltage across the capacitor equals the battery voltage and the current is zero. (Again, this assumes an ideal capacitor in which charge will not leak across the dielectric.) Note that the current is maximum when the voltage changes the fastest, and current is minimum when the rate of change of voltage is a minimum.

Figure 6-11 illustrates the relationsl ip between instantaneous voltage, current, and power in a purely capacitive circuit. Note that as the voltage passes through zero, the current is at its peak. When the voltage is at its peak, the current is zero. Again, although voltage and current have the same frequency, they are offset in phase by 90 degrees. In a purely capacitive circuit *current leads the voltage* by 90 degrees. This relationship is characteristic of all purely capacitive circuits.

Figure 6-11 shows that the average power consumed in this circuit is also zero. Like the inductor, the capacitor acts as a source of power during one quarter cycle and a consumer of power in the next quarter cycle. Real power is zero but *reactive power* is being exchanged back and forth between the circuit and capacitor. What is happening in the capacitor is that energy is alternately being stored in the electric field of the capacitor and then returned back to the circuit. In a *purely capacitive circuit*, the reactive power can also by calculated by

$$Q = EI,$$

where

Q = reactive power (VAR),
E = source voltage (volts), and
I = source current (amps).

Compare Figures 6-9 and 6-11. If the frequencies and voltage sources are the same, the inductor gives energy back to the circuit on the same quarter cycle that the capacitor removes (stores) energy from the circuit. This 180 degree difference results from the fact that current lags by 90 degrees in an inductor and leads by 90 degrees in a capacitor. In the specification of reactive power we recognize this distinction by labeling reactive power associated with a capacitor as negative and that associated with an inductor as positive. It should be apparent then, if a circuit contains both inductive and capacitive elements, the positive reactive power will cancel or offset the negative reactive power. Whether they cancel or one just offsets the other is a function of the size of the respective capcitances and inductances.

Finally, as was the case with inductors, circuits may exhibit properties of capacitance even though they do not contain capacitors. For example, wire cables lying side by side separated by insulation and through which current flows exhibit capacitive properties.

6.3.2.5 Capacitive Reactance

Capacitive reactance is the opposition by a capacitor, or capacitive circuit, to the flow of current. The current flowing in a capacitive circuit is directly proportional to the capacitance and to the rate at which the applied voltage is changing. The rate at which the voltage changes is determined by the frequency. Therefore, if the frequency is increased, the current flow will increase. It can also be said that if the frequency or capacitance is increased, the opposition to current flow decreases. Therefore, capacitive reactance, which is the opposition to current flow, is inversely proportional to frequency and capacitance. Capacitive reactance, X_C, is measured in ohms, as is inductive reactance, and can be calculated by:

$$X_C = \frac{1}{2\pi fC},$$

where

f = frequency in Hz,
π = 3.14, and
C = capacitance (farads).

The current that flows in a circuit with only capacitive reactance is:

$$I = \frac{E}{X_C}$$

where

I = effective current (A),
E = effective voltage across the capacitive reactance, and
X_C = capacitive reactance (Ω).

Note that capacitive reactance decreases as frequency increases and is 180 degrees out of phase with inductive reactance.

6.3.3 Real Power in Complex Circuits

Most circuits are neither purely resistive, purely inductive, nor purely capacitive. Instead, they contain a combination of all three elements or exhibit properties of all three elements. This situation is represented by showing the three elements in series as seen in Figure 6-12. In this case, voltage and current are not in phase as they were in a purely resistive circuit, nor are they exactly 90 degrees out of phase. Also, there is both real power (as a result of the resistor) and reactive power (as a result of the inductor and the capacitor). In the illustrated circuit, and in AC circuits in general, the power supplied by the source can be expressed as the product of voltage times current, modified by the degree to which voltage and current are in phase.

The relative angle between the voltage and current in an AC circuit is measured in degrees and is referred to as the phase angle (θ). In Figure 6-12, for example, current lags voltage by 30 degrees, making the absolute value of the phase angle:

$$\theta = 30 \text{ degrees}.$$

Given phase angle (the angle by which voltage and current are out of phase), the degree or extent to which voltage and current are in phase can be calculated by:

$$pf = \text{cosine}(\theta),$$

where

pf = the power factor, which represents the degree to which voltage and current are in phase, and

θ = the phase angle.

Using the power factor relationship, we can express the general equation for real power in a single phase AC circuit as

$$P = EI\text{cosine}(\theta),$$

where

P = real power (watts),
E = source voltage (volts),
I = current out of the source (amps), and
cosine (θ) = the circuit or load power factor.

Note that E and I are rms quantities.

6.3.4 Reactive Power in Complex Circuits

Reactive power in complex circuits is calculated in a similar manner to real power, except it is a function of the degree to which voltage and current are *90 degrees out of phase* with each other. For the complex AC circuit of Figure 6-12, we can calculate reactive power by:

$$Q = EI\text{sine}(\theta),$$

where now

sine (θ) represents the extent to which voltage and current are 90 degrees out of phase.

6.3.5 Impedance

In complex circuits containing elements that are both resistive (resistors) and reactive (inductors and/or capacitors), the total opposition to current flow is called impedance (Z) and is measured in ohms. Because the reactive elements affect both the phase angle and the magnitude of the current in a complex circuit, impedance is a complex quantity with both a magnitude (ohms) and an associated impedance angle. Impedance values are usually written in polar (or phasor) form (i.e., $Z \angle \Phi$), where Φ is the impedance angle.

The overall impedance of a circuit is calculated by combining the resistance and reactances of each circuit element, either in series or in parallel. Because of the need to account for angular relationships, this calculation is best accomplished in a simple series circuit using vector addition as shown in Figure 6-13. In Figure 6-13, the vector sum of the resistance and reactances is 5 ohms with an impedance angle of about 37 degrees.

Impedance values can be used in Ohm's law to calculate voltage or current in AC circuits with the following equations:

$$E = IZ \text{ or } I = E/Z \text{ or } Z = E/I$$

Applying Ohm's law to the circuit in Figure 6-13 results in a calculated current of 20 amps and a phase angle with an absolute value of 37 degrees. Note that the impedance angle and phase angle are equal in magnitude. Note also that the inductive reactance is larger than the capacitive reactance in this circuit, so the overall circuit is inductive in nature with current lagging voltage.

6.3.6 Power Triangles

The relationship between real power and reactive power for either a source (generator) or a load may be shown using a power triangle. A power triangle is constructed in a coordinate system where reactive power in VARs is on the vertical axis; real power in watts is on the horizontal axis. Reactive power associated with inductive loads is drawn in the positive direction and reactive power associated with capacitive loads is drawn in the negative direction. This coordinate system is shown in Figure 6-14A.

Figure 6-14B is a power triangle for a load consisting primarily of resistive and inductive elements (note that the reactive power is positive). Note that the hypotenuse of the triangle is labeled apparent power. Apparent power is defined as the voltage across the load times the current into the load and has units of volt-amps (VA). Only in circuits with no net reactive components (reactive power equals zero) is the apparent power equal to the real power. Similarly, only in circuits with no resistive components is the apparent power equal to the reactive power.

From the equations of real and reactive power, note that the angle between true power and apparent power on the power triangle representation is the phase angle (θ).

The utility of power triangles can be seen from the example shown in Figure 6-15. A generator is supplying two loads in parallel, each load consisting of some resistance and some reactance. In load 1 assume that the generator is supplying 500 watts and 300 VARs; in load 2, assume 200 watts and -50 VARs. The question is, at what power factor does the generator operate?

At the bottom of Figure 6-15, the power triangles are drawn for the two loads and the generator. Note that the total power of the loads equals the real power supplied by the generator, and the net reactive power of the loads equals the reactive power supplied by the generator. Knowing the components of the generator's power triangle, it is a simple matter to then calculate the phase angle and the power factor as shown at the bottom of Figure 6-15.

From this example, it should be evident that a purely capacitive load of -250 VARs could be added that would "cancel" the entire net reactive load of 250 VARs. This would improve the power factor (make it closer to unity) and reduce the magnitude of the current that must be supplied by the generator. This is referred to as power factor correction and is a technique used by consumers of large amounts of power to reduce the current they draw and consequently the amount these consumers must spend for electric power.

6.3.7 Leading and Lagging Power Factors

The power factor must be stipulated as being either *leading* or *lagging*.

- A circuit with predominantly capacitive reactance (negative reactive power) has a leading power factor. (Current *leads* voltage.)
- A circuit with predominately inductive reactance (positive reactive power) has a lagging power factor. (Current *lags* voltage.)
- A circuit with no reactive elements or equal capacitive and inductive elements has a power factor equal to 1 (unity power factor).

In the example above and Figure 6-15, a complete specification of power factor would be 0.94 *lagging*.

6.4 Three Phase Systems

Most of the generation, transmission, and heavy-power utilization of electrical energy involves polyphase systems, i.e., systems in which several sources equal in magnitude but differing in phase from each other are available. Because it possesses definite economic and operating advantages, the three-phase system is by far the most common. A three-phase source is one that has available three equal voltages, which are 120 degrees out of phase with each other. As we shall see in Chapter 7, all three voltages are usually generated in the same machine. A three-phase load is one which can utilize the output of a three-phase source. Three voltage sources forming a three-phase system are shown in Figure 6-16A.

There are two possibilities for connecting the three phases of either a load or a generator. These are shown in Figures 6-16B and C. Terminals a', b', and c' may be joined to form the neutral o, yielding a *wye connection*, or terminals a and b'; b and c', and c and a' may be joined individually, yielding a delta *connection*. In the wye connection, a neutral *conductor*, shown dotted in Figure 6-16B, may or may not be brought out. If a neutral conductor exists, the system is a *four-wire three-*

phase system; if not, it is a *three-wire three-phase system*. Wye connected systems are frequently found on generators. In the delta connection (see Figure 6-16C), no neutral exists and only a three-wire three-phase system can be formed.

The three phase voltages, as shown in Figure 6-16A, are equal and phase-displaced by 120 electrical degrees, a general characteristic of a *balanced three-phase system*. Furthermore, the impedance in any one phase is equal to that in either of the other two phases, so that the resulting phase currents are equal and phase-displaced from each other by 120 electrical degrees. Likewise, equal power and equal reactive power flow in each phase. An *unbalanced three-phase system*, on the other hand, may lack any or all of these equalities and 120 degree displacements. Significantly, unbalanced three-phase systems are not desired and are uncommon. Many industrial loads are three-phase loads and are, therefore, inherently balanced. In supplying single-phase loads from a three-phase source, definite efforts are made to keep the three-phase system balanced by assigning approximately equal single-phase loads to each of the three phases.

Three-phase systems are advantageous for several reasons. Because the total circuit power is divided among three conductors, three-phase systems may use smaller wires than single phase systems with the same capacity and are, therefore, more economical. As we will learn in Chapter 7, three-phase power may be generated relatively easily in a single generator simply by adding two more phases to the generator armature. Many large loads (motors) operate more smoothly and efficiently using three-phase power. The instantaneous power for any balanced three-phase system is constant. This is of particular advantage in the operation of three-phase motors for it means that shaft power output is constant, and the torque pulsations leading toward motor vibration do not occur as a result of the motor supply system.

6.4.1 Phase and Line Relationships in Three-Phase Systems

In three-phase systems, it is important to know the relationship between phase and line quantities. This particularly applies to three-phase generators. The phase voltage and currents are the voltages across and through a single phase and can be thought of as internal to the machine. Assuming a balanced system, the three-phase voltages and currents will be equal in magnitude and differ by 120 degrees.

Line voltage and current are external to the machine, on the lines between a generator and a load or between loads or generators. This nomenclature is illustrated in Figures 6-16B and C. Note that line voltage is often referred to as terminal voltage.

In wye connected systems, the line current is identically equal to the phase current. However, line voltage is greater than phase voltage by a factor of $\sqrt{3}$ or 1.73. This number can be derived by applying Kirchoff's voltage law around a loop containing the wye connection and taking into account the angular relationships between the phase voltages and currents. These relationships for a wye connected system can be represented by the following equations:

$$I_{LY} = I_{\phi Y}$$

$$V_{L_Y} = \sqrt{3}\, V_{\phi_Y}$$

where

I_{LY} = line current,
$I_{\phi Y}$ = phase current,
V_{LY} = line voltage, and
$V_{\phi Y}$ = phase voltage.

In a delta connected system, the line voltage is identically equal to the phase voltage. However, line current is greater than phase current by a factor of $\sqrt{3}$. The following equations represent this relationship:

$$V_{L_\Delta} = V_{\phi_\Delta}$$

$$I_{L_\Delta} = \sqrt{3}\, I_{\phi_\Delta}$$

where

$V_{L\Delta}$ = line voltage,
$V_{\phi\Delta}$ = phase voltage,
$I_{L\Delta}$ = line current, and
$I_{\phi\Delta}$ = phase current.

6.4.2 Power in Three-Phase Systems

In a balanced three-phase system, the total instantaneous power is constant and equal to three times the average power per phase. This relationship between average and instantaneous power is illustrated in Figure 6-17. Using this relationship, the total real power in a three-phase system can be expressed in terms of the line voltage and current as shown below:

$$P_\phi = V_\phi I_\phi \cos\theta$$

$$P_{TOT} = 3V_\phi I_\phi \cos\theta$$

Assuming a wye-connected system and expressing voltage and current in terms of line values:

$$P_{TOT} = 3\frac{V_L}{\sqrt{3}} I_L \cos\theta$$

which reduces to:

$$P_{TOT} = \sqrt{3}\, V_L I_L \cos\theta$$

This is the general expression for power in a balanced three-phase system. It should be apparent that the assumption of a delta-connected system would yield the same expression.

6.4.3 Grounded Three-Phase Systems

Three-phase power systems may be operated grounded or ungrounded. The grounded system may include a fourth neutral conductor, which carries only the unbalanced current, if any. The windings in transformers, generators, and other three-phase equipment may be connected together in wye or delta form. Usually, the delta connection is used in ungrounded systems, and the wye in grounded systems, with the common or neutral point connected to ground and/or the neutral conductor. The neutral conductor operates essentially at ground potential if the three-phase loads are balanced.

The grounded system provides two voltage levels: line-to-line voltage (480 V in the common 480-V system) and line-to-ground or line-to-neutral voltage. Line-to-ground voltage = 1/ $\sqrt{3}$ or 0.57 x line-to-line voltage. Typical four-wire systems provide 480/277 V for power and lighting or 208/120 V.

If a ground fault develops on one of the phase conductors, a ground protection relay immediately detects the large unbalance curent in the neutral and trips a circuit breaker, isolating the fault and cutting off power to the process.

The ungrounded system has a fixed line-to-line voltage only. In the event that a ground fault develops on one conductor, that conductor falls to ground potential, while the potential of the other two conductors rises to the line-to-line voltage above ground. If the fault current is small, which is often the case, the system can continue to operate until a time when the ground fault can be located and repaired. This is why the ungrounded system is preferred by many plant operators.

Problems arise only if the ground fault is left unrepaired -- eventually, a second ground fault occurs on another phase in another part of the system. The result is a much more destructive line-to-line fault (at the higher line voltage), which damages equipment in two parts of the system.

An additional problem that can occur with ungrounded systems is overstressing of insulation. Even with a low-level fault, the two unfaulted conductors are raised above their rated potential. If a high-level fault occurs, transient voltages are generated as the fault arc strikes and restrikes, and in the circuit breaker as it operates to clear the fault. These transient voltages impose much higher stresses on the conductor insulation of the ungrounded system.

The resistance-grounded system is preferred by many industries. In this case, the neutral is grounded, not solidly, but through a resistance. The size of this resistance is selected so that, if a ground fault occurs, the current flowing through the neutral will be large enough to trip the ground-fault relay, but not so large that the fault arc can do serious damage, such as destroying motor laminations.

Utilities prefer large ground-fault currents that ensure unambiguous operation of ground-fault relays. In addition, solidly grounded systems allow the utilities to use grounded-neutral lightning arresters, which are less expensive and more effective than ungrounded arresters.

6.5 Transformers

Transformers are devices that make use of electromagnetic induction to change or transform voltages from one value to another. Like any other device, a transformer cannot produce more power than it takes in. When voltage is stepped up, current is stepped down proportionately.

Transformers are capable of stepping up an AC voltage to very high values, permitting the transmission of large amounts of power over long cables without undue I^2R losses. By stepping up the voltage at the generator to values close to a half million volts, the current sent over the power line can be relatively small for a given amount of required power, permitting a reduction in the size of the cables. At the receiving end of the power line, the voltage is then reduced by *step-down* transformer to a value suitable for homes, offices, and factories.

A transformer consists essentially of two coils wrapped around the same metal core and coupled by electromagnetic inductance (see Figure 6-18). The coils are electrically insulated from each other, but are linked by common magnetic flux through the metal core. One coil, the primary winding, is connected to the AC voltage supply (generator), while the other coil, called the secondary winding, is connected to a load, which may be any electrical device. The transformer thus transfers electrical energy from the primary circuit to the secondary circuit without a direct connection and permits at the same time a step-up or step-down of the primary voltage or current.

The fact that there are no electrical connections between the primary and secondary sides of a transformer allows it to be used as an isolation device. Electrical faults (grounds) on one circuit (primary) will not be "seen" by another circuit (secondary) that is isolated by a transformer.

6.5.1 Theory of Operation

With the primary winding connected to an AC supply, the alternations of the primary current set up a *changing* magnetic field in the core that is continually expanding, collapsing, and building up again in the opposite direction. This changing flux induces an alternating (AC) voltage in the secondary winding, which can supply a current to a closed secondary circuit. The variations in the flux, which produce the secondary voltage, also affect the primary winding (due to its self-inductance). This induces a voltage referred to as counter emf that opposes the current AC (and the voltage) applied to the primary winding. The value of this counter emf is *almost equal* to the applied voltage when no current is drawn from the secondary winding and very little current flows through the primary under no-load conditions. The small current that does flow is known as the no-load or magnetizing current, because it magnetizes the core. When a current is drawn by the secondary load, a proportional current flows through the primary. If the primary of a transformer is connected to a DC voltage, a voltage is induced in the secondary for the *instant* during which the magnetic field is building up, but this voltage collapses immediately, as soon as the field reaches a steady (unchanging) value. Because of the absence of a counter emf for DC, the primary current will be large. Also because the resistance of the winding is small, the primary winding will burn out due to I^2R losses. Therefore, the transformer is strictly an AC device.

6.5.2 Ideal Transformers

In a transformer having a closed iron core, practically all the lines of force produced by the primary winding link every turn of the secondary winding and the flux leakage is almost zero. A transformer without flux leakage transfers all the energy from the primary to the secondary winding and, for this reason, is called an ideal transformer. Some of the larger commercial transformers come close to being ideal transformers. Typical transformers are greater than 98% efficient.

A few simple relations hold for ideal transformers, which are approximately correct for most practical transformers. For example, the voltage induced in the primary winding (E_p) is proportional to the number of turns of the primary (N_p) and the rate of change of the magnetic flux across the primary winding $\left(\frac{d\phi_p}{dt}\right)$.

This relationship can be expressed as follows:

$$E_p = N_p\left(\frac{d\phi_p}{dt}\right).$$

A similar expression can be written for the voltage induced in the secondary windings

$$E_s = N_s\left(\frac{d\phi_s}{dt}\right).$$

Since the primary and secondary are linked by the same magnetic flux,

$$\frac{d\phi_p}{dt} = \frac{d\phi_s}{dt}.$$

The voltage induced in the primary can be related to the voltage induced in the secondary by the ratio of turns in the primary to turns in the secondary:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s},$$

where E_p and E_s are the primary and secondary voltages, respectively, and N_p and N_s are the number of primary and secondary turns, respectively.

If no energy is lost by flux leakage (and other causes), the power output of an ideal transformer must be the *same* as the power input to the primary winding. Hence, we can write:

$$E_pI_p = E_sI_s$$

or

$$\frac{I_p}{I_s} = \frac{E_s}{E_p}$$

but from the previous relation:

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

Substituting:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}.$$

Stated in words, the primary-to-secondary current ratio is equal to the reciprocal of the primary-to-secondary turns ratio. By comparison with the previous formula, it is apparent that the current is stepped down whenever the voltage is stepped up, and vice versa.

6.5.3 The Autotransformer

In addition to the many applications of transformers in power distribution and electronics, one unconventional type of transformer combines the primary and secondary into a single tapped winding (see Figure 6-19). This arrangement is called an autotransformer. Either step-up or step-down voltage ratios may be obtained. The type illustrated in Figure 6-19 is a step-down transformer because the input voltage is applied across the entire winding, serving as primary, while the output voltage is taken from the portion of the winding included between one end and the tap. The autotransformer does not provide isolation between primary and secondary circuits, but its simplicity makes it economical and space-saving. Autotransformers are used in some of the motor control circuits (see Chapter 9).

Chapter 6 Definitions

RESISTANCE (R) - The name given to the opposition to the movement of electrical current through a given material. This opposition results in the conversion of electrical energy into heat. All materials offer some opposition to the flow of electrical current, and there is no material in which some current cannot be produced, although it may be minute.

INDUCTANCE (L) - The property of a circuit that causes a voltage to be induced in the circuit by a change of the current flow in the circuit.

INDUCTIVE REACTANCE (X_L) - The opposition to the flow of changing current due to inductance.

CAPACITANCE (C) - The phenomenon whereby a circuit stores electrical energy in a capacitor. Whenever two conducting materials are separated by an insulating material, they have the ability to store electrical energy. A capacitor connected to an AC circuit experiences a constantly changing voltage; therefore, current will flow first in one direction, charging the capacitor, and then in the opposite direction, discharging the capacitor.

CAPACITIVE REACTANCE (X_C) - The opposition to the flow of changing current due to capacitance.

REAL POWER (P) - Power is the rate of doing work, or the rate of delivering electrical energy to a working component. Real power (sometimes called true power) is the name given to the term measured in watts (W) to distinguish it from other power terms (i.e., apparent power, reactive power).

REACTIVE POWER (Q) - The name given to describe the average power transfer of energy alternatingly being stored in a circuit and then transferred back to the circuit. Expressed in (VAR) volt-amps-reactive.

APPARENT POWER - The term applied to the product of voltage and current in an AC circuit. Also, the vector sum of reactive power and the real (true) power. Expressed in (VA) volt-amperes.

POWER FACTOR (Pf) - The ratio of the true power (watts) to the apparent power (volt-amperes). Power factor is expressed as a decimal or as a percentage. Power factor should be stated as to whether it is leading or lagging (the relationship of the current to the voltage).

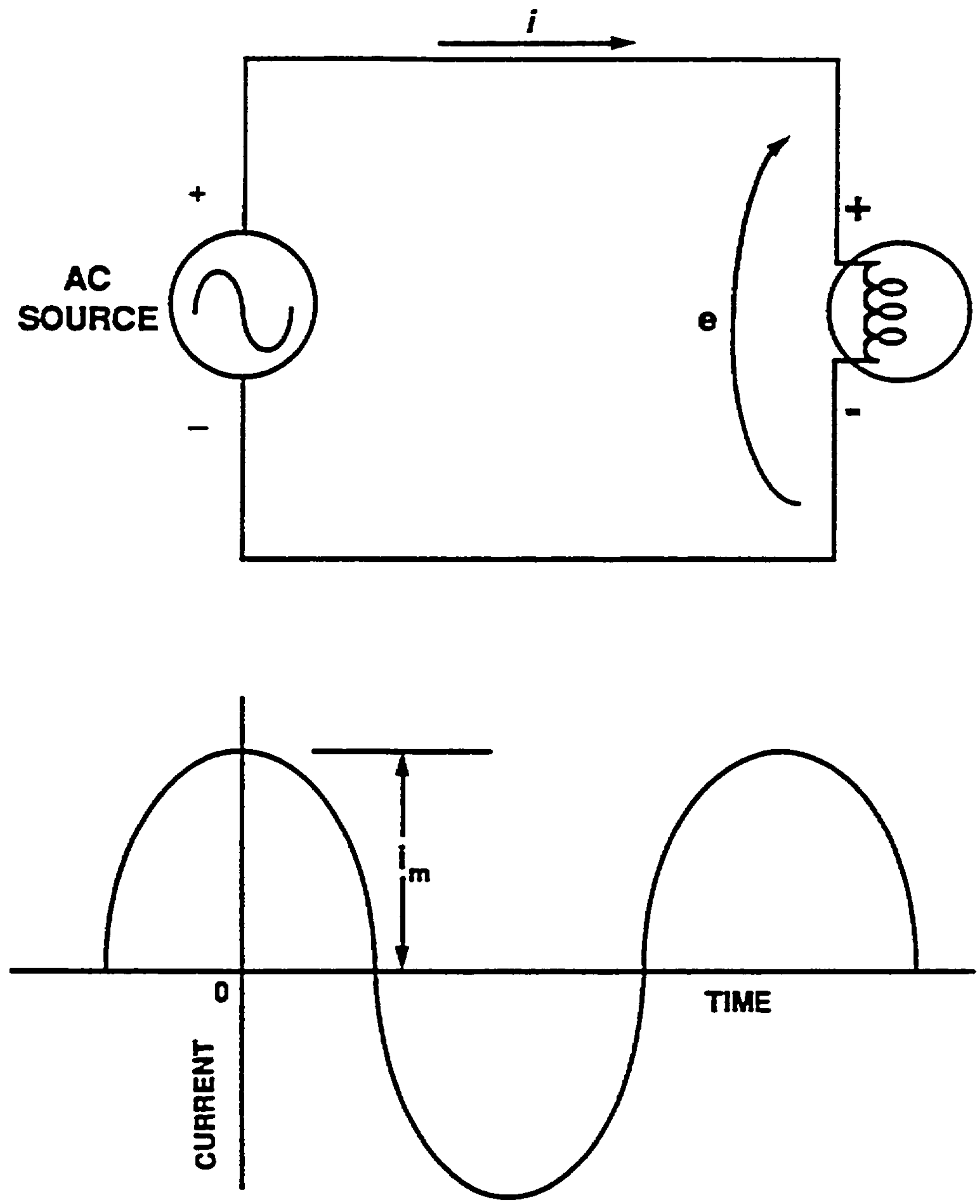


Figure 6-1. Graph of Alternating Current in an AC Circuit

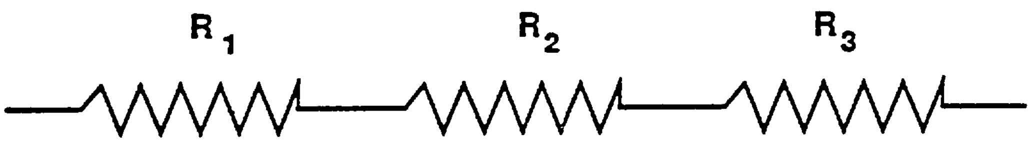


Figure 6-2A. Resistors in Series

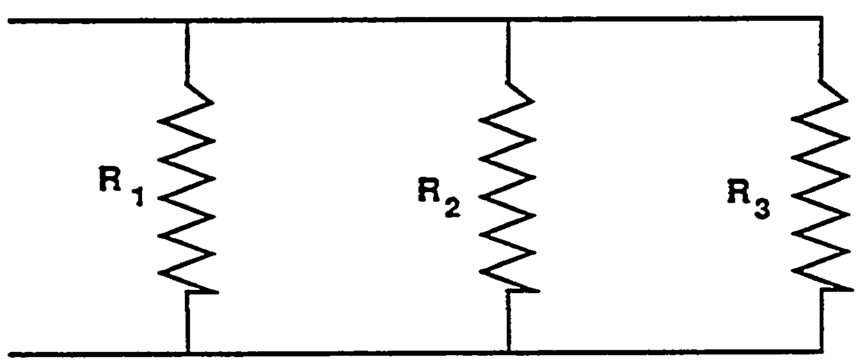


Figure 6-2B. Resistors in Parallel

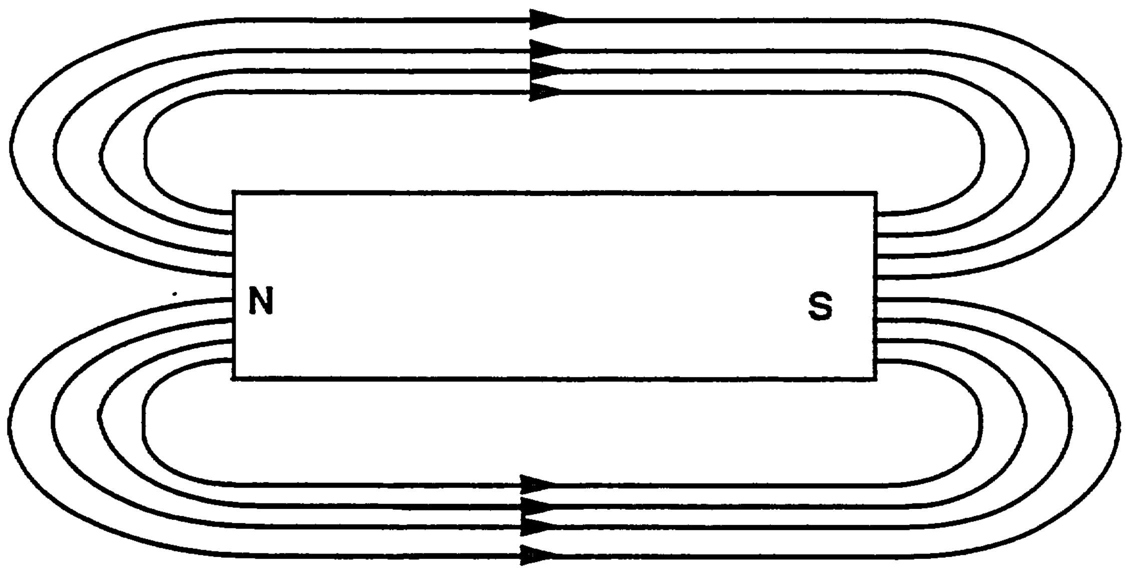


Figure 6-3. Direction of Magnetic Field is from North to South Pole

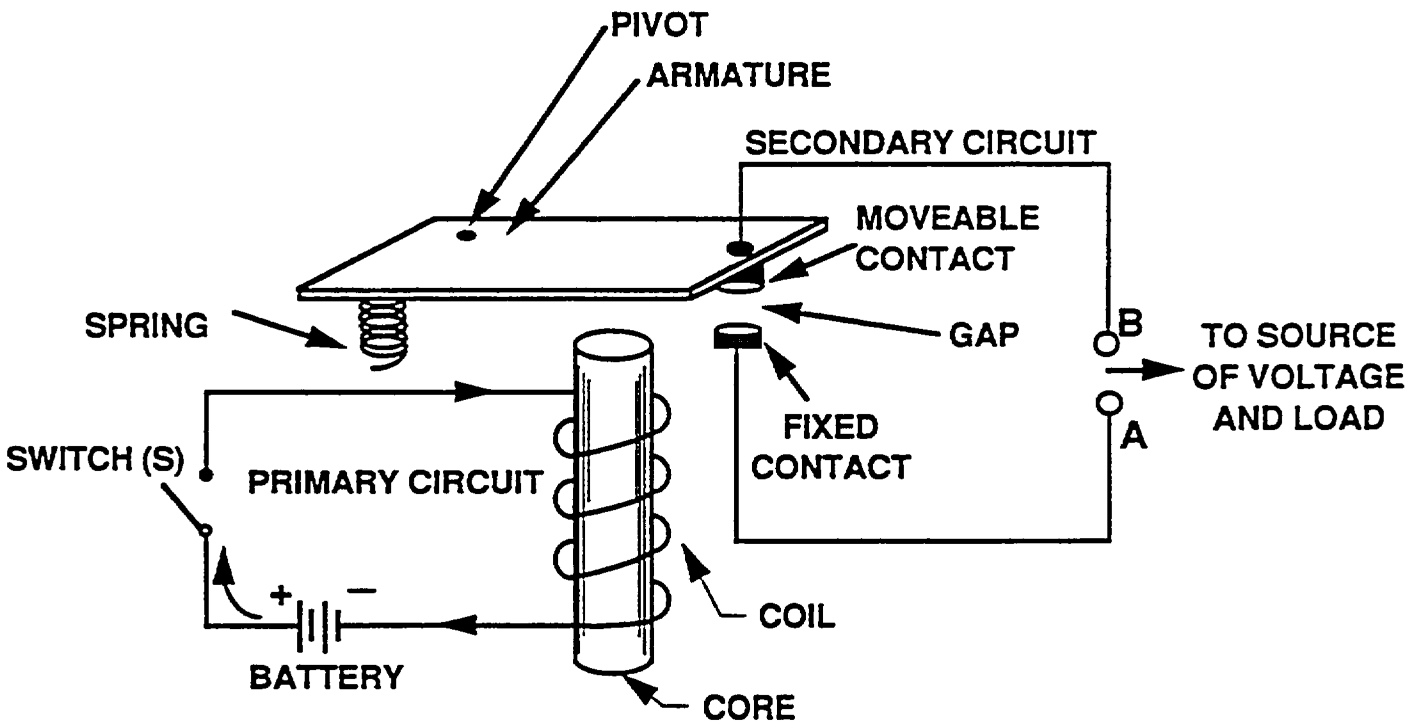


Figure 6-4. Schematic Presentation of Relay and Associated Circuits

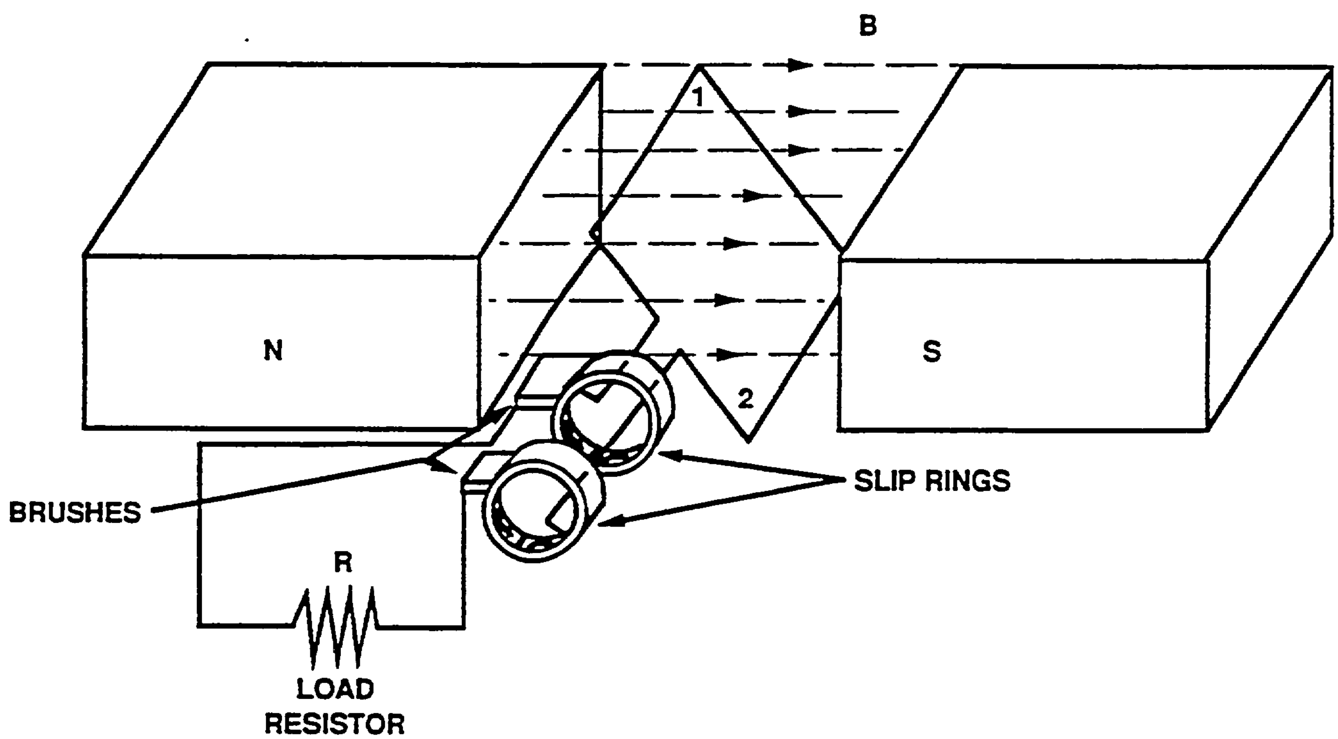


Figure 6-5. Two Pole AC Generator

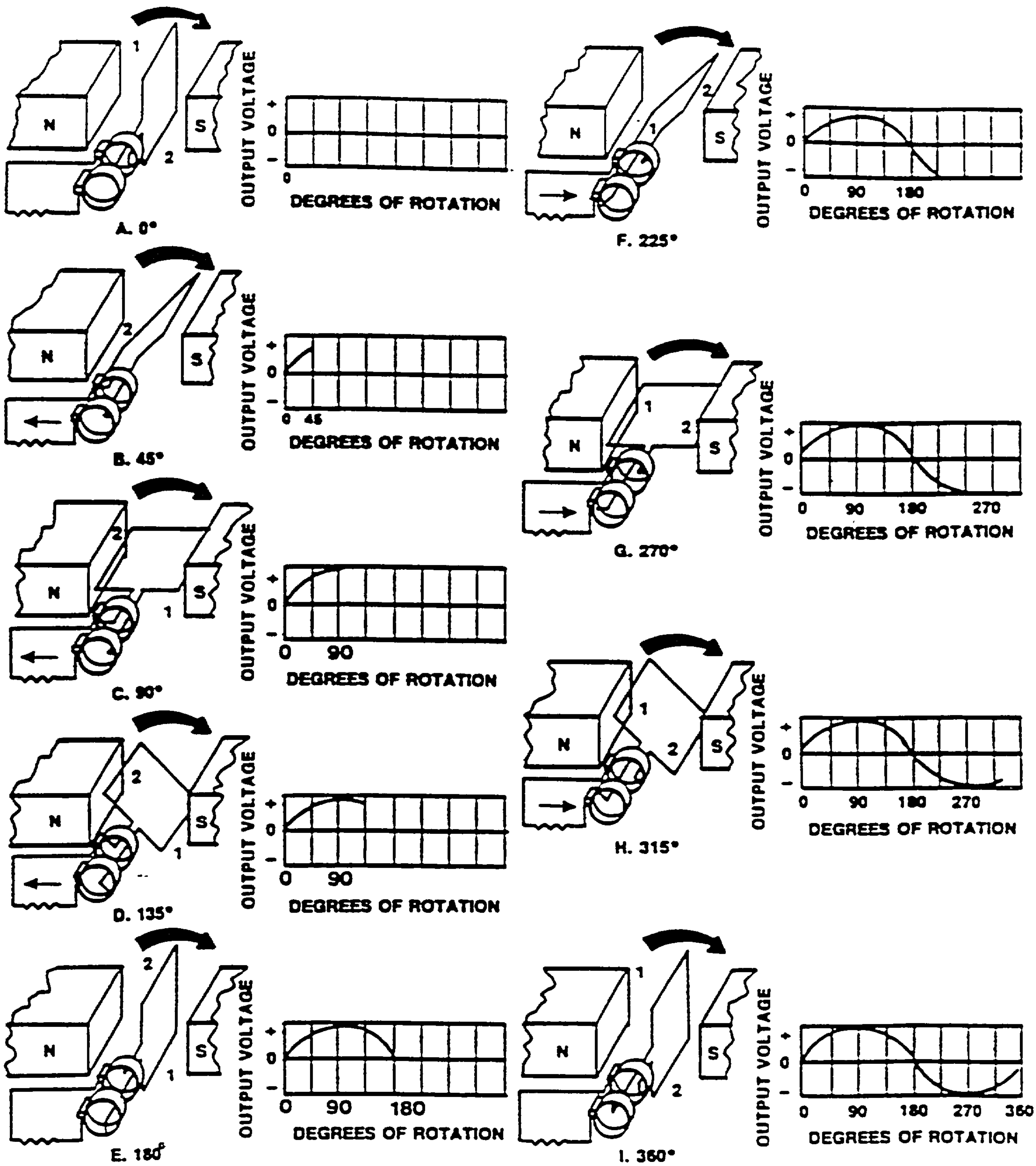


Figure 6-6. Generation of a Sine Wave

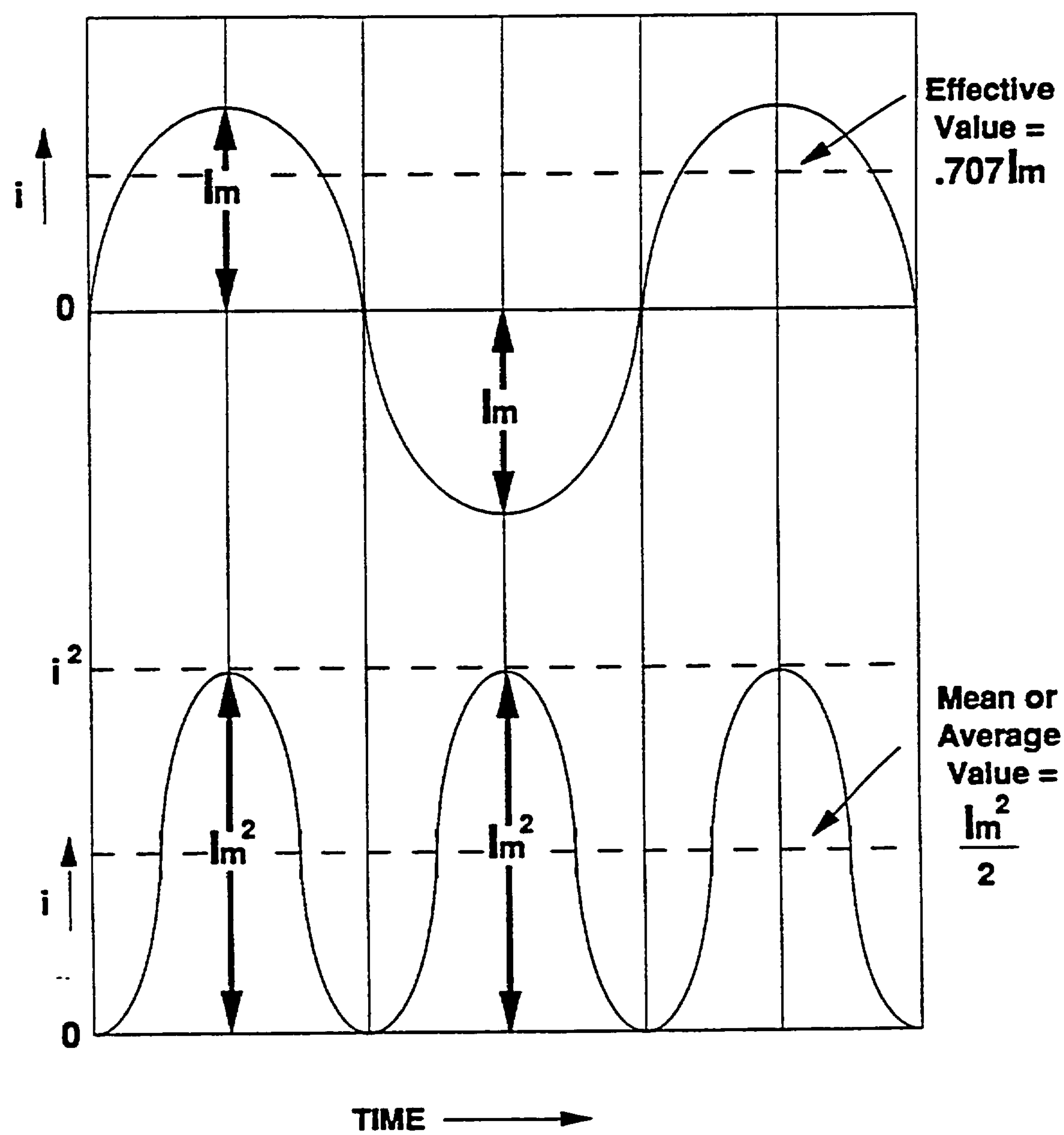


Figure 6-7. Determining the Effective Value of an Alternating Current

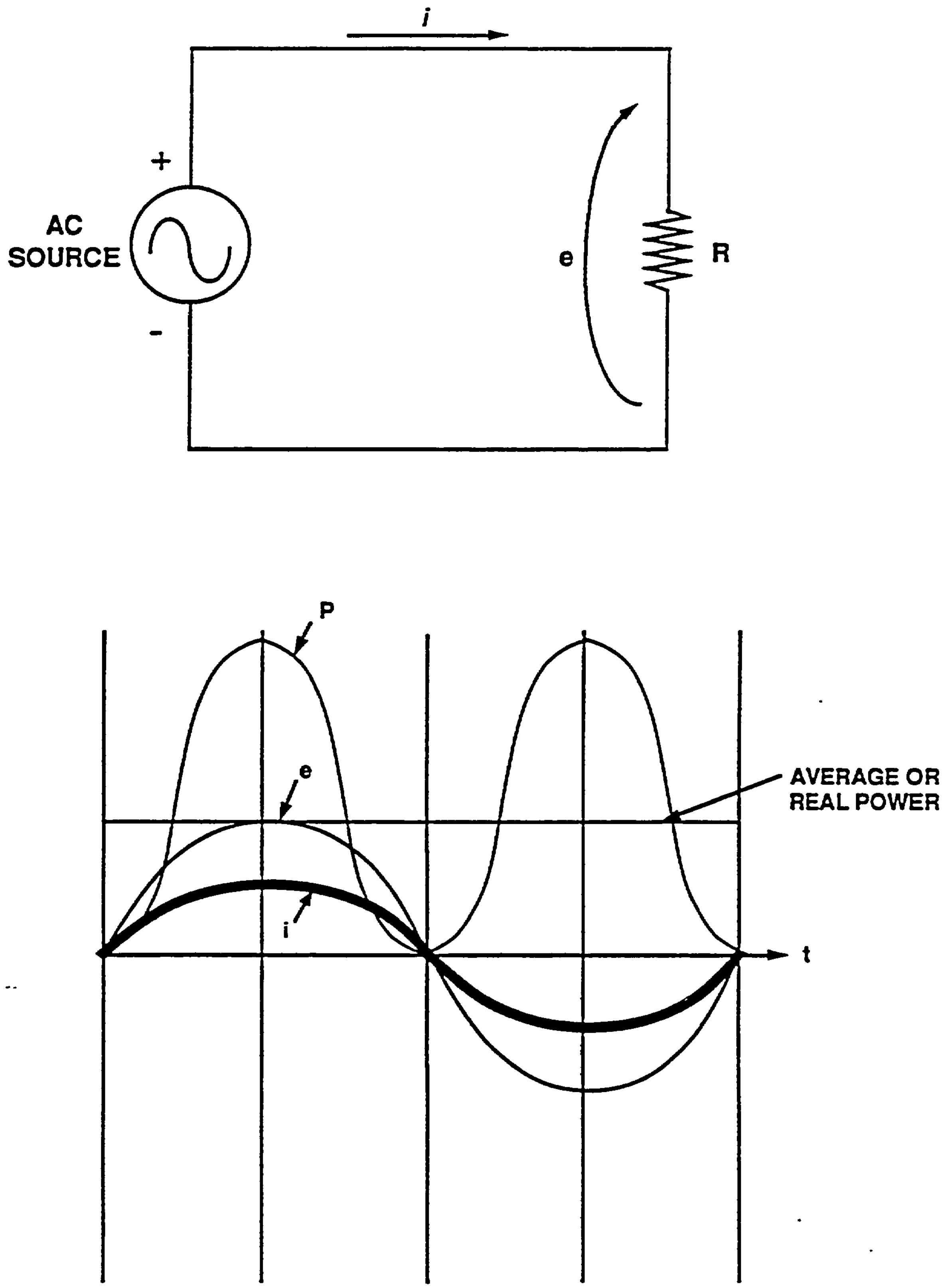


Figure 6-8. Real Power in a Purely Resistive Circuit

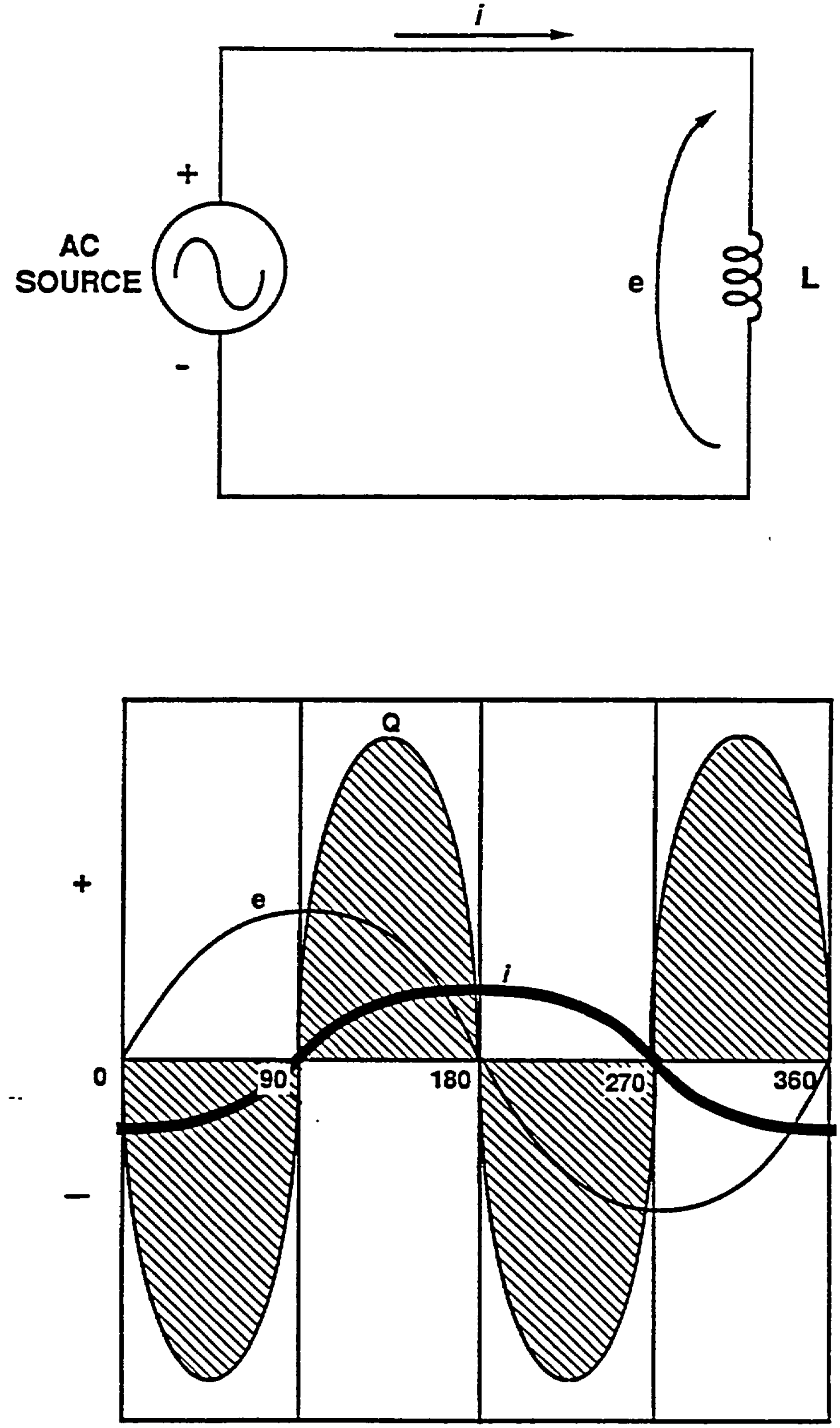
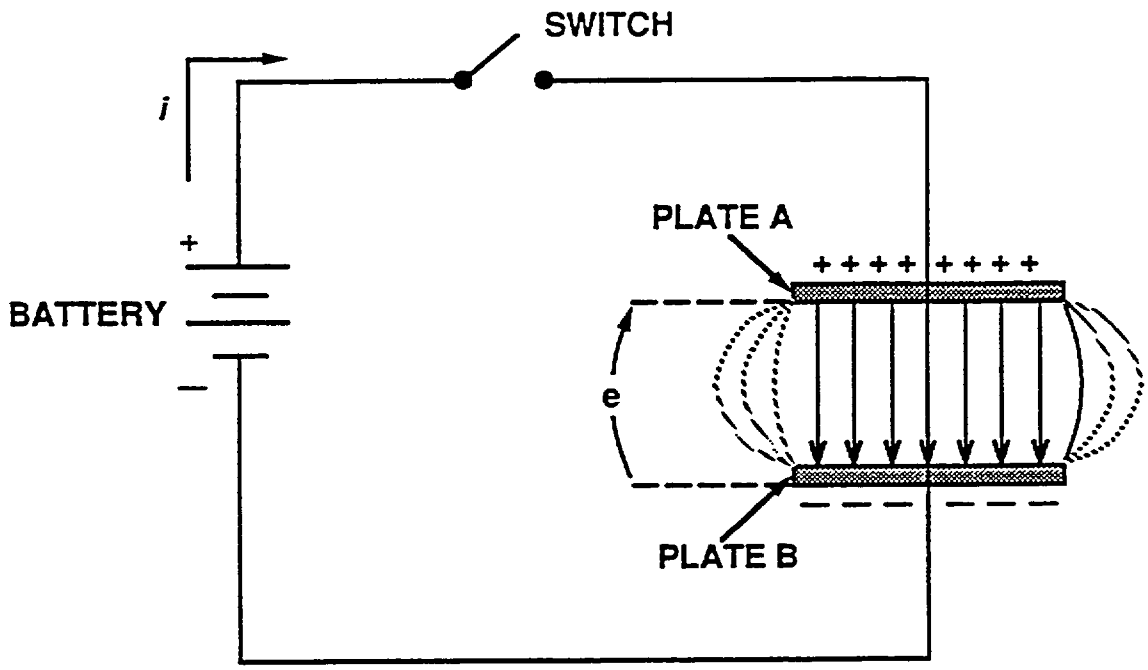


Figure 6-9. Reactive Power in a Purely Inductive Circuit



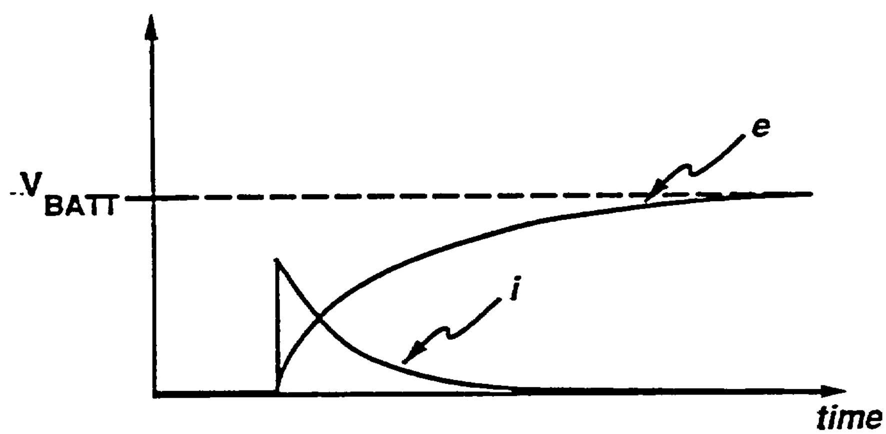


Figure 6-10. Principle of Parallel Plate Capacitor

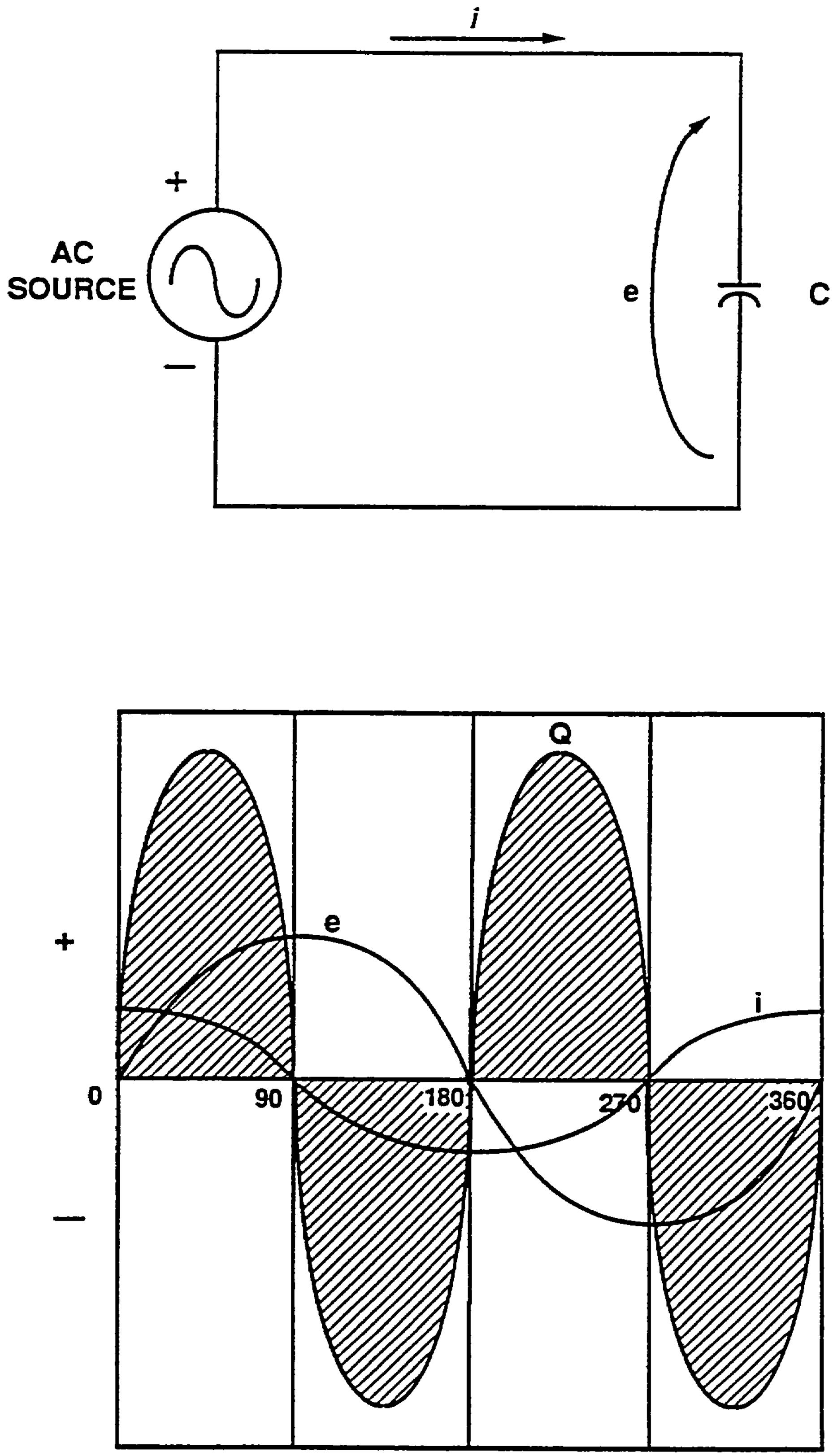


Figure 6-11. Reactive Power in a Purely Capacitive Circuit

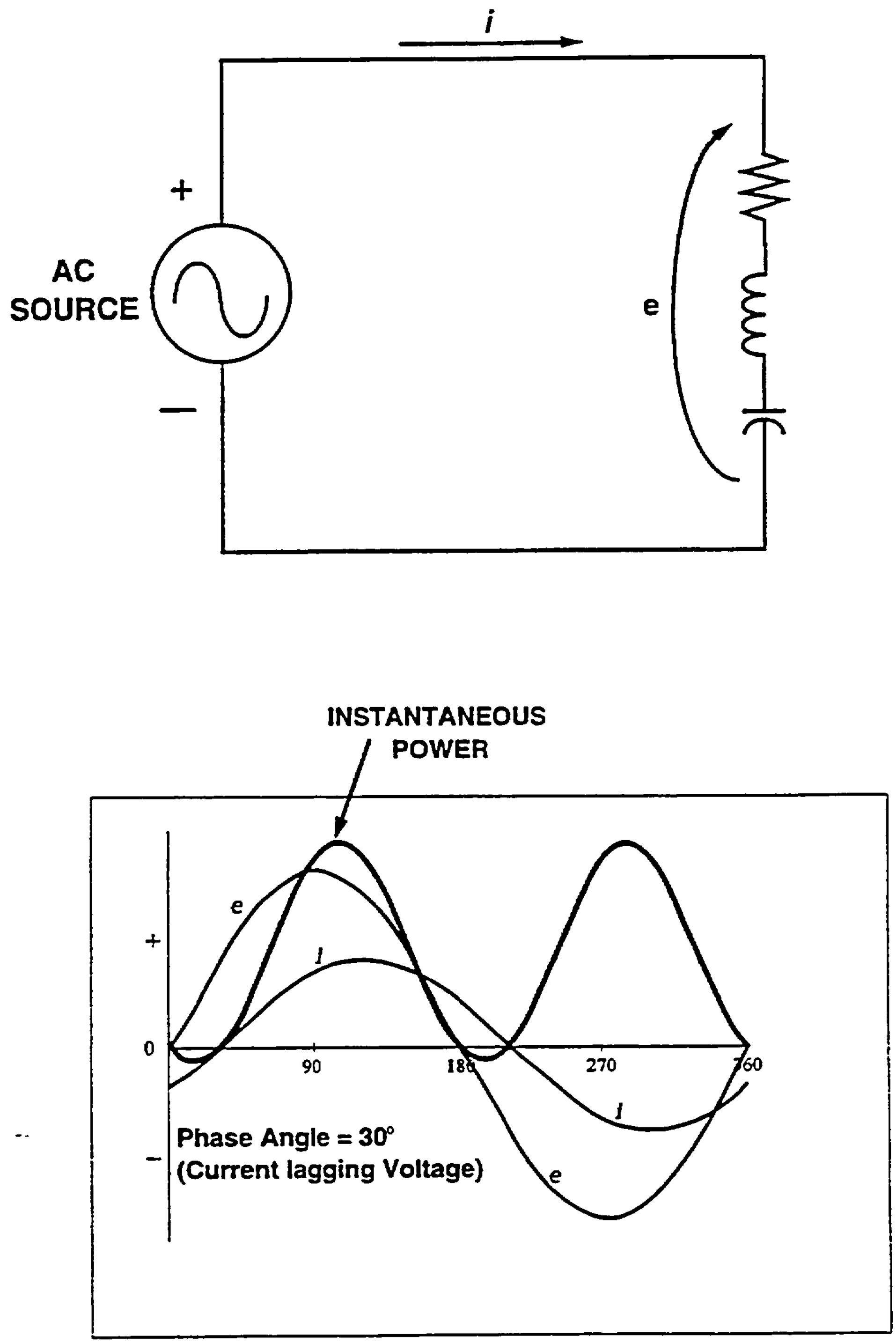
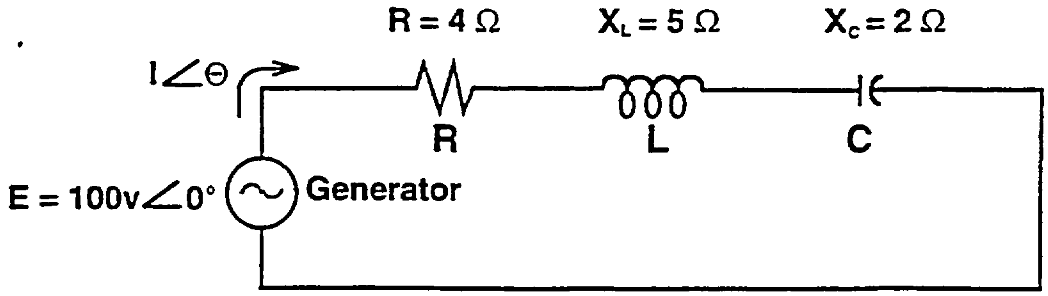
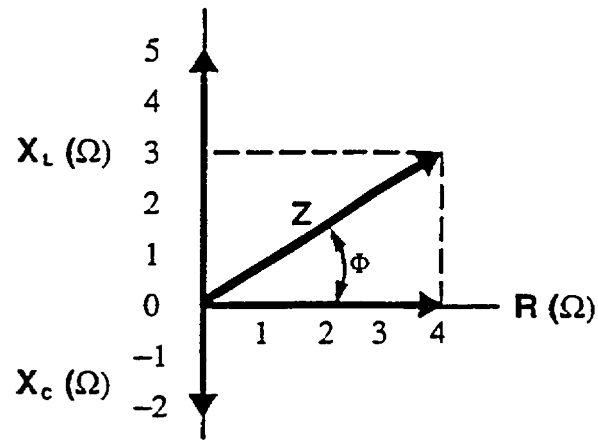


Figure 6-12. Complex AC Circuit



Vector Diagram
for Impedance and
Impedance Angle



Solving the vector diagram mathematically yields the following:

$$|Z| = \sqrt{R^2 + (X_L - X_C)^2}$$

$$|Z| = \sqrt{4^2 + (5 - 2)^2} = 5\ \Omega$$

$$\Phi = \tan^{-1}\frac{(X_L - X_C)}{R}$$

$$\Phi = \tan^{-1}\left(\frac{3}{4}\right) = 37^\circ$$

Therefore, $Z = 5\ \Omega \angle 37^\circ$

Applying Ohm's Law for AC Circuits:

$$I = \frac{E}{Z} = \frac{100\text{v}\angle 0^\circ}{5\ \Omega\angle 37^\circ}$$

I = 20 amps with a 37° phase angle (Current lagging Voltage)

Figure 6-13. Impedance in AC Circuits

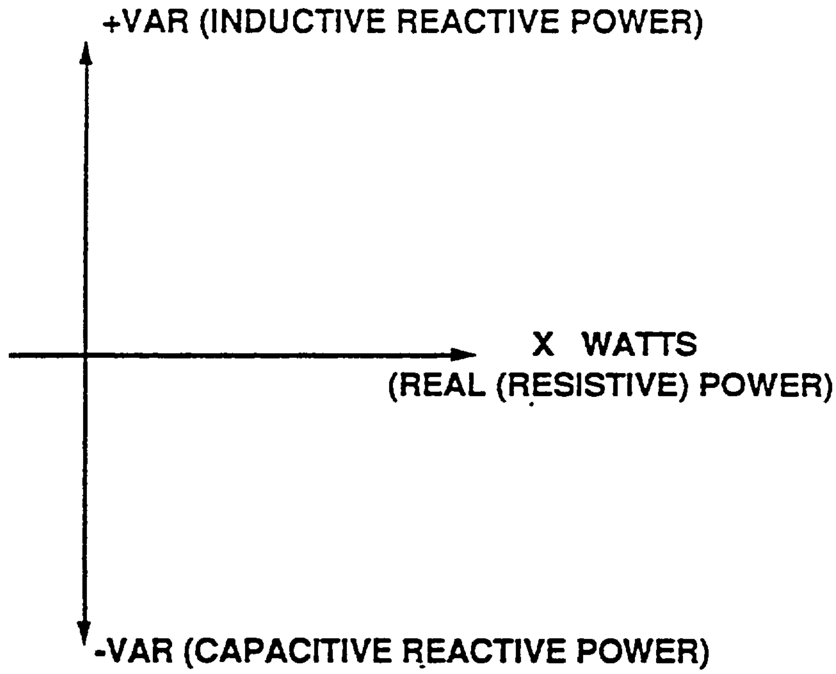


Figure 6-14A. General Plot of Power Components

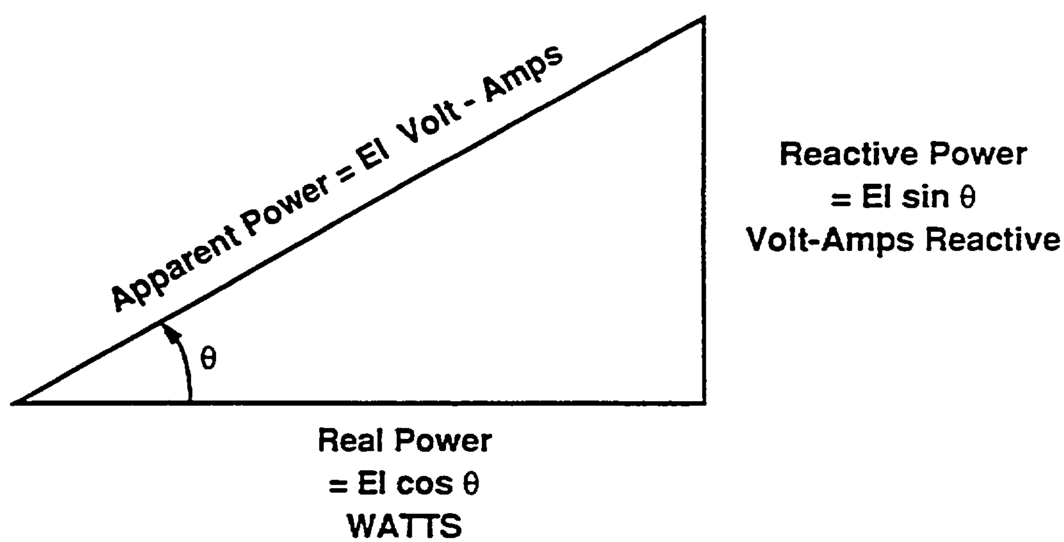
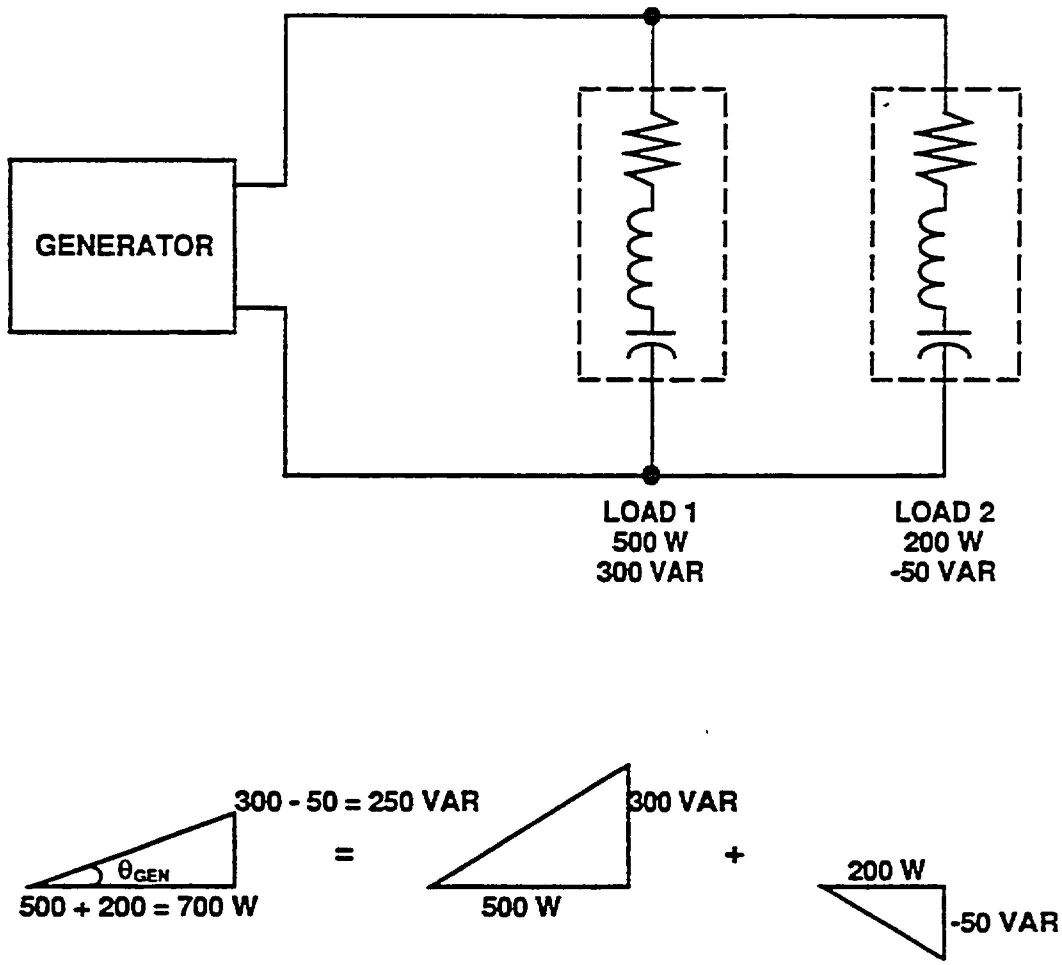


Figure 6-14B. Power Triangle



$$\theta_{GEN} = \mathrm{TAN}^{-1}\left(\frac{250}{700}\right) = 19.7 \text{ degrees}$$

Power Factor of generator = COS(19.7) = 0.94 lagging

Figure 6-15. Application of Power Triangle

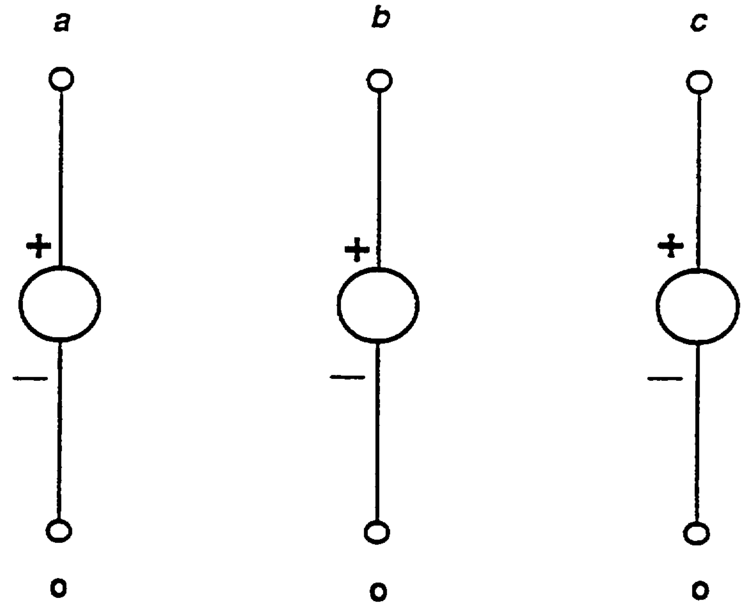


Figure 6-16A. Three-phase Source

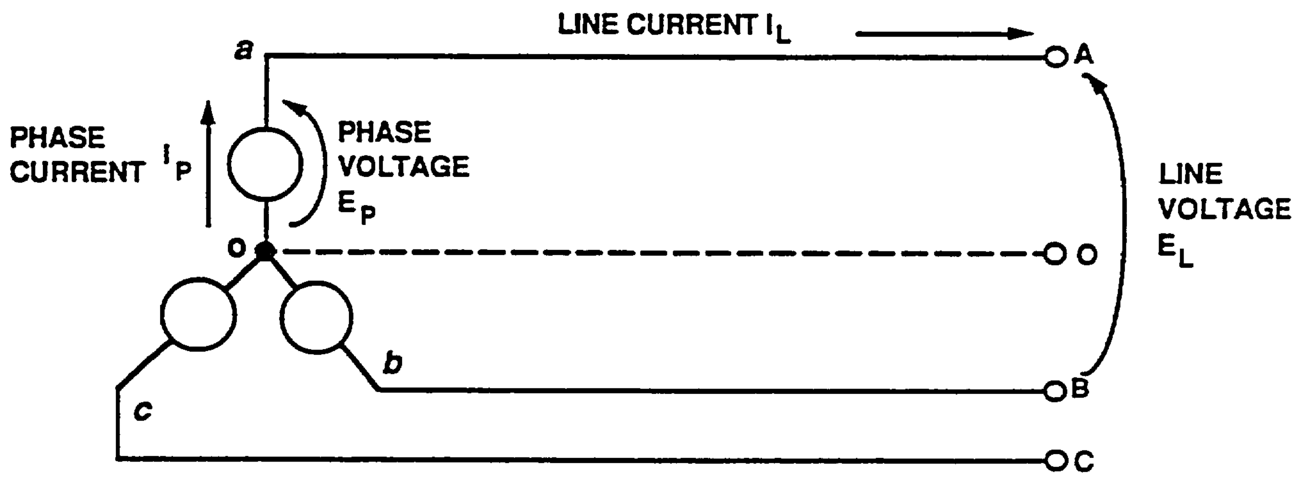


Figure 6-16B. Wye Connection

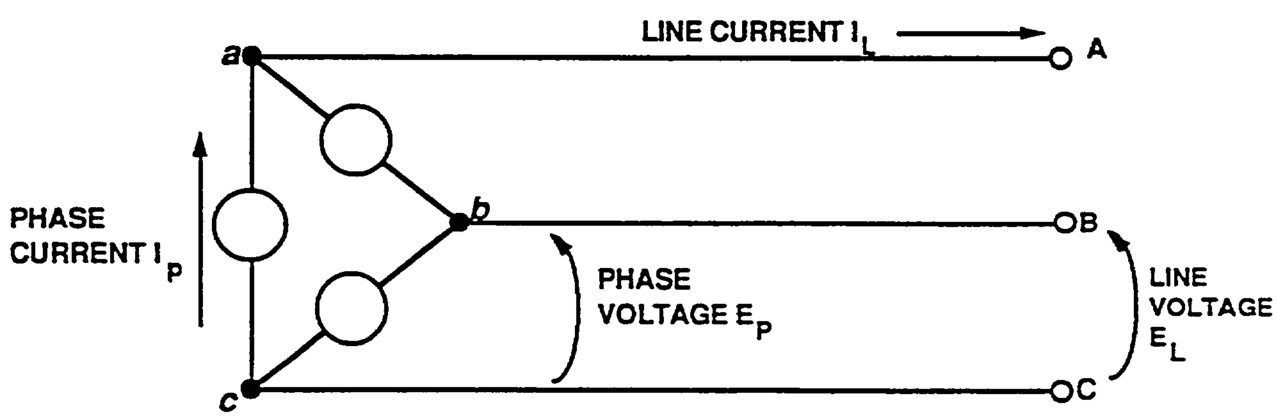


Figure 6-16C. Delta Connection

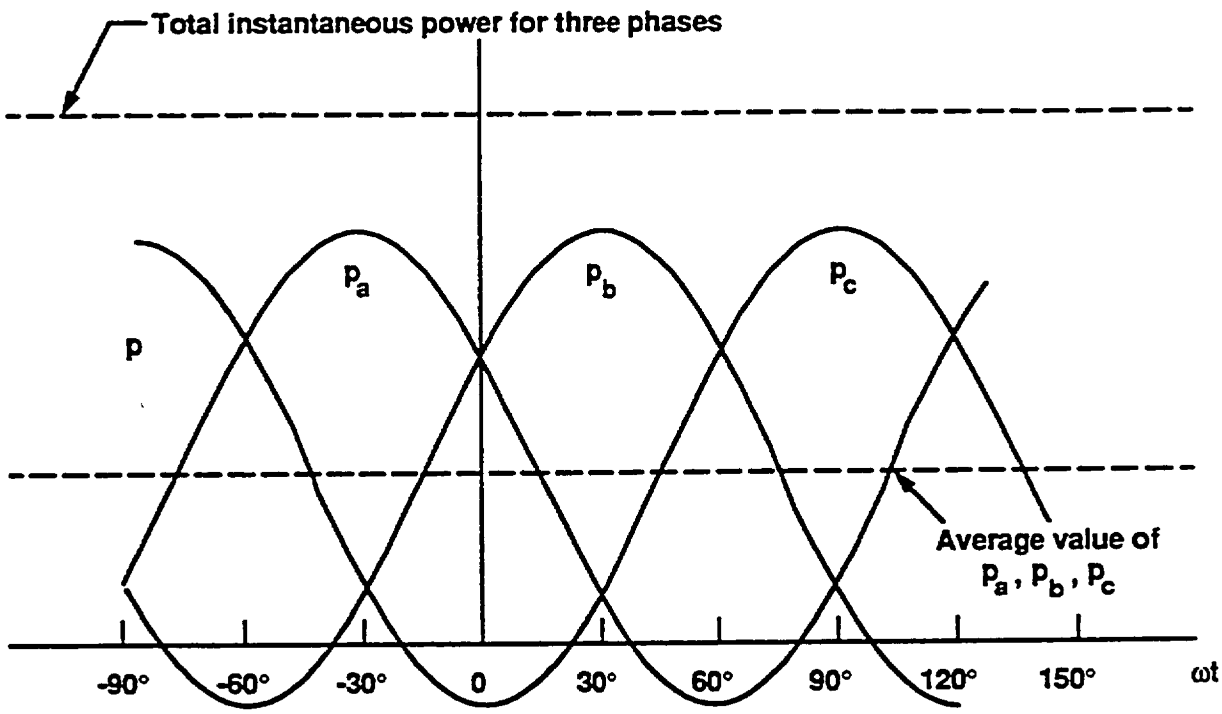


Figure 6-17. Instantaneous Power in a Three-Phase System

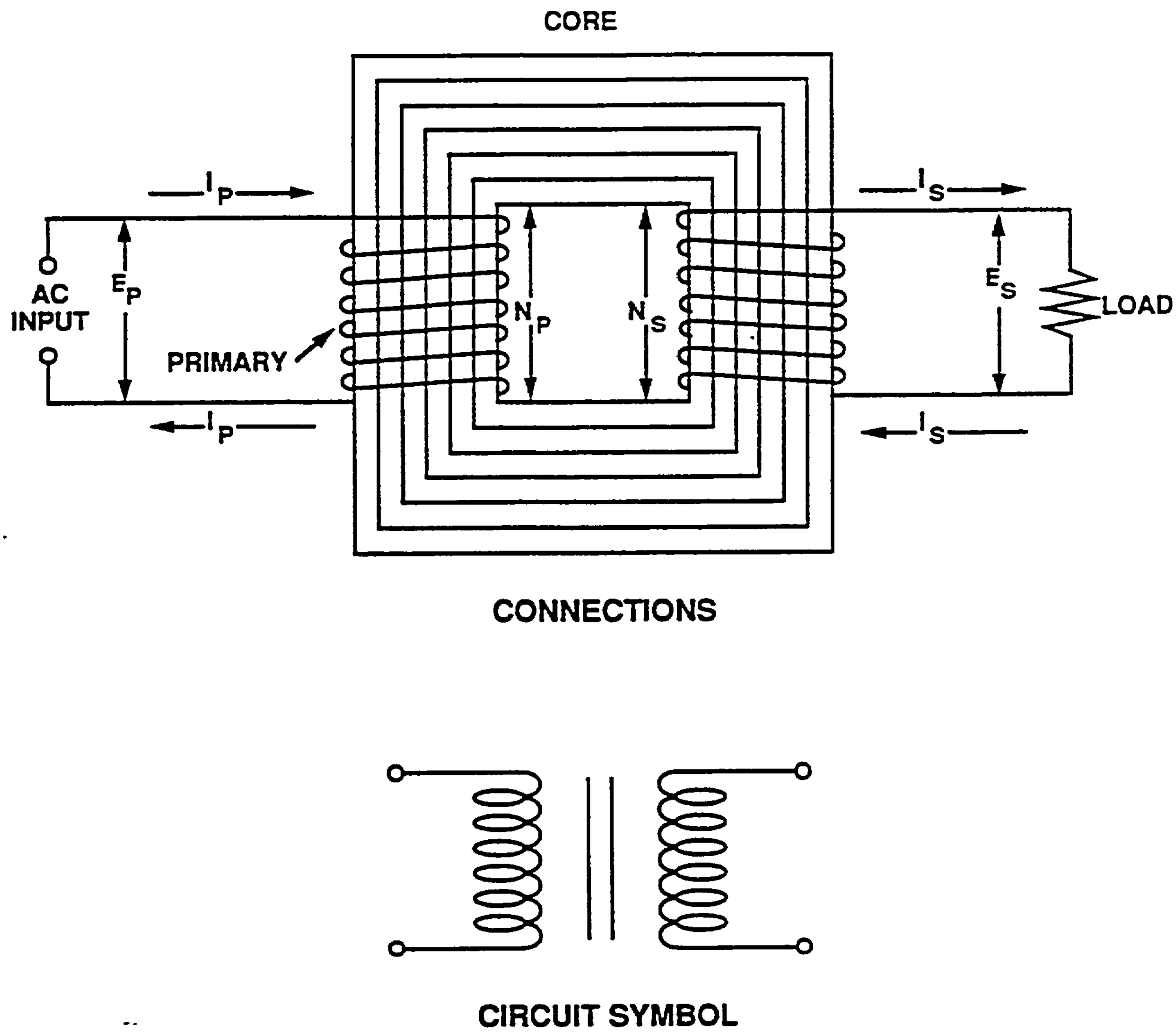


Figure 6-18. Elements of Simple Transformer

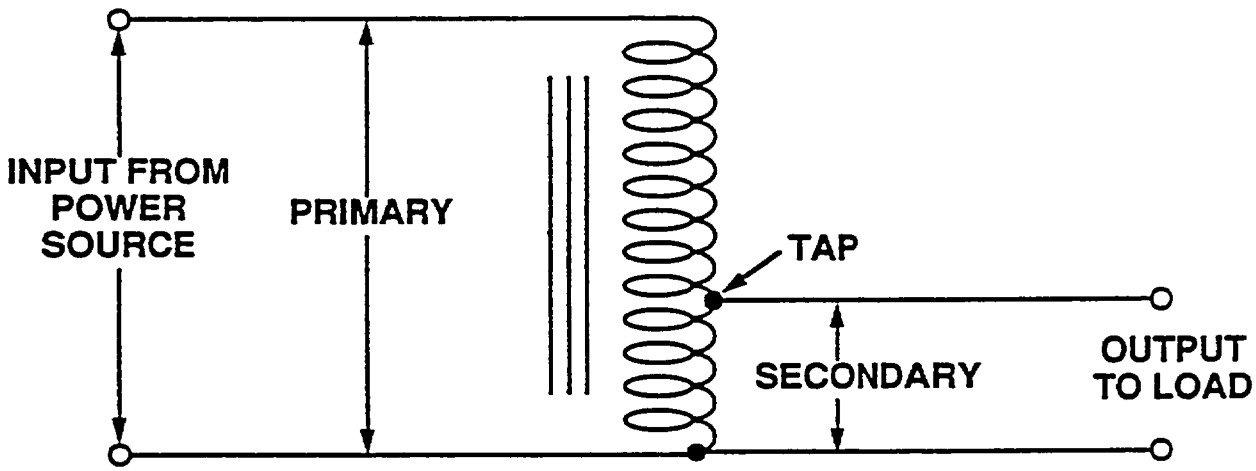


Figure 6-19. Schematic Diagram of Step-Down Autotransformer

7.0 GENERATORS

Learning Objectives

After studying this chapter, you should be able to:

1. Explain the conditions necessary to produce voltage in a generator.
2. State the relationship between generator frequency and speed.
3. Define the following terms:
   a. Field
   b. Armature
   c. Stator
   d. Rotor
4. Explain how generator terminal voltage and frequency are controlled.
5. Explain what determines the power factor for an independent generator supplying various loads.
6. Explain what determines the power factor for a generator on an infinite bus.
7. Describe how real load is changed for a generator on an infinite bus.
8. Describe the three conditions that must be met in order to parallel a generator with an infinite bus.
9. Explain the limitations associated with generator operation.

7.1 Introduction

Alternating current (AC) has definite advantages over direct current (DC). Low voltage DC cannot be transmitted economically over long distances because of the large power losses on the transmission line (I^2R). On the other hand, AC can be easily converted to high voltage, low current at its source for transmission, and then converted to the voltage required by the load. Low current during transmission results in low I^2R losses. Because of this unique ability of AC, most electrical power for commercial use is generated by AC generators.

All generators operate on the same basic principles. To generate a voltage, there must be a *magnetic field, a conductor, and relative motion between the two.* The stationary part of a generator is called the stator, and the moving part is the rotor. The magnetic field is generated by current in the field windings. The conductor in which the voltage is induced is the armature. To satisfy the requirement for relative motion, the armature can be on either the stator or the rotor. If the magnetic field is generated in the stator windings, and the armature is on the rotor, the armature current path must be connected from the rotor to the transmission lines by slip rings. Because the currents in the armature are high, there would be considerable loss at the slip rings, which are high resistance points. The answer to this problem is to have the rotor generate the magnetic field and make the stator the armature. Even if slip rings are used to connect the rotor windings to a current source to produce a magnetic field, the field currents are much lower than armature currents. This type of generator, a revolving field generator, is the one most often used in commercial applications and will be the only one discussed in this chapter.

7.2 Polyphase and Multiple Pole Generators

Figure 7-1 illustrates an end view of a simple two pole, single phase revolving field generator and its output. Two magnetic poles are created on the rotor by the application of direct current to the field windings on the rotor. Because the rotor is turning and the direct current is normally supplied from outside the machine, this DC field input must be applied to the rotor using slip rings and brushes.

Because this is a single phase generator, there is a single loop of armature windings 180 degrees apart embedded in the stator. Note that you can trace the armature circuit from the AC output terminal, T_1, to the beginning of the winding on top of the stator and back along the inside edge of the stator (into the page in Figure 7-1). From there the circuit goes across the back of the stator and then along the bottom of the stator (out of the page) and to the output terminal, T_2. Note that in practical generators, there may be many armature windings in each phase and not just a single one as in this example.

Relative motion is provided by mechanically rotating the rotor, in this example in a counter-clockwise direction. The bottom of Figure 7-1 shows the sine wave which is produced at the terminals T_1 and T_2 as the rotor is rotated 360 degrees. Note that the peak voltage is produced as the magnetic poles pass in front of the armature windings and there is a maximum amount relative motion between the armature conductors and the magnetic lines of flux.

A three phase AC generator can be created by using three sets of armature windings, 120 degrees apart. This is illustrated in Figure 7-2A and B. The outputs can be sent to three separate loads using six lines or the coils can be connected together in a delta or wye configuration to make a three or four wire system. Most commercial power is generated as three phase.

Figure 7-1 shows that for each full rotation of the field, the output will complete one full electrical cycle. To produce 60 Hz power, the rotor would have to turn at 60 revolutions per second, which is 3600 rpm. To run the machine at a slower speed and still produce 60 Hz output, more poles can be added to the field, as in Figure 7-3. As the rotor makes a full rotation, the output will complete two electrical cycles. This is a four pole rotor, and only requires 1800 rpm to produce 60 Hz power. The relationship between speed and frequency is expressed by the following:

$$N = \frac{120f}{p}$$

where

N = speed in rpm,
f = frequency in Hz (cycles per second), and
p = number of poles.

Note that the number of poles must be even, and the maximum number of stator coils is equal to the product of the number of phases and the number of poles.

7.3 Generator Construction

Because most utilities use revolving field generators, the descriptions below are for this type machine. In this design, electricity is produced by rotating a magnetic field (rotor) through a conductor (stator). The rotational (mechanical) energy is supplied by the turbine, and the magnetic field is supplied by *exciting* the rotor. The *exciter* provides the current needed to produce the magnetic field in the rotor, making it a large electromagnet. The stator, the rotor, and the exciter are the three main components of a generator.

7.3.1 The Stator (or Armature)

The stator is the stationary part of any generator. The armature is the part of the machine in which voltage is induced; thus, in a revolving field generator, the *armature is on the stator*. A simplified stator is shown in Figure 7-4, consisting of a frame, a stator core, and armature windings or stator bars.

The stator frame is a gas-tight casing that supports and encloses the stator, the rotor, and other generator components. The generator's gas coolant (usually hydrogen in large generators) is contained in the frame and is circulated by fans attached to each end of the rotor. A separate water cooling system is also provided for the stator.

The stator core consists of thousands of thin, segmental punchings of steel. The punchings are assembled on key bars into a cylindrical steel core. The punchings are grouped into packages and separated by spacers to allow for ventilation; they have radial slots for the stator bars and dovetail slots for assembly and locking purposes. The assembled punchings are placed into the frame; the key bars lock the assembled stator into the stator frame as shown on Figure 7-4.

The stator bars (Figure 7-5) make up the stator (or armature) winding. This is the conductor that will be cut by the moving magnetic field set up by exciting the rotor windings. The armature winding is made by inserting the copper stator bars into the radial slots of the punchings. The bars are insulated from the punchings. The winding is completed by joining the ends of the stator bars in the proper order to form three complete conductor coils.

Figure 7-5 shows the assembly of the stator bar into the stator core slots. The bars are made up of copper strands; each strand is hollow to carry the cooling liquid. Oil is sometimes used for cooling in older units; modern units always use deionized water.

Resistance temperature detectors are placed between the stator bars in the stator winding to measure the temperature. The temperature is measured at the point where it will be the highest to ensure adequate cooling to the entire stator winding.

7.3.2 The Rotor

The rotor provides the moving magnetic field in a generator. A simplified rotor is shown in Figure 7-6. Because it will be turning at such high speed (usually 1800 rpm), it is important that the rotor be sturdily constructed. Wherever possible, one-piece forgings are used for the rotor. Slots to hold the rotor windings are milled into the rotor forging.

The rotor is simply a large electromagnet. The rotor forging is the core of the magnet, and the rotor windings provide the current to produce the magnetic field. The current is provided by the exciter. The rotor windings are insulated conductor bars that fit into the slots in the rotor forging. The ends of the windings are attached with end turns in an order to produce the proper magnetic field. To prevent the end turns from becoming disconnected by centrifugal force, retaining rings are placed on the ends of the rotor. A collector assembly is used to conduct the excitation current from the stationary exciter to the turning rotor. The collector rings are grooved in a helical manner to remove dust and worn ring material and to help cool the brushes.

7.3.3 Exciter

It was stated earlier that the rotor is an electromagnet, that is, a core of conductive material with windings wrapped around it. When a current is passed through the windings, a magnetic field is set up around the core. To create the proper magnetic field, the exciter must provide direct current to the rotor windings.

One basic type of excitation system is the AC alternator with the DC rectifier. The principles behind this type of excitation system are typical of other excitation systems. One type of system uses a separate shaft-driven AC alternator to provide excitation (see Figure 7-7). The AC alternator is contained in a housing at the end of the main generator. DC rectifiers in the housing convert AC into the DC needed for main generator excitation. The alternator is a small, air-cooled generator; it is referred to as an "alternator" to avoid confusion with the main generator. Water coolers are used to cool the alternator air. The DC rectifiers are also often water cooled.

The excitation system controls the current to the rotor. The amount of current determines the strength of the magnetic field, and thus generator voltage. As the load increases, the rotor's resistance to rotation increases, and the turbine control valves open to maintain generator speed. The excitation current automatically increases to maintain constant voltage at the generator terminals.

Referring to figure 7-7, the output of the alternator is rectified in the rectifier assembly and supplied to the main field of the generator through the main collectors. The alternator output is also rectified within the alemator field circuit assembly and used to provide its own field excitation. Hence, the alternator is self-excited. Note that the alternator field is supplied via the exciter alternator collectors and is either increased or decreased by the output of the voltage regulator. The regulator senses main generator output and responds by increasing or decreasing the alternator field current. When the generator is started, the alternator field is "flashed" from a separate power supply and then the process is self-sustaining.

7.3.4 Brushless Exciter

A refinement in excitation systems is the brushless exciter. It is designed so that all high power components are mounted on the shaft, and it eliminates the carbon brushes and collector rings of earlier designs. The brushless exciter shown in Figure 7-8 employs all solid-state circuitry. The assembly is completely housed in a self-ventilated enclosure and consists of three basic parts: a permanent magnet pilot exciter, a main AC exciter, and a rectifier wheel.

The high frequency permanent magnet generator provides power to the automatic voltage regulator that regulates and controls the output of the exciter to control the generator voltage.

The AC output from the rotating exciter armature is fed along the shaft to silicon diodes mounted on the rotating diode wheels. The exciter output is thus rectified and the resultant DC current is carried by rotating components on the shaft to the main generator field winding.

The system is protected against diode failure by series connected fuses having indicating devices that may be inspected during operation. The diodes and fuses are arranged in modular construction for ease of maintenance.

7.4 <u>Generator Auxiliary Systems</u>

Several systems relating to generator cooling will be discussed in this section. They are the stator cooling water system, hydrogen cooling system, hydrogen seal oil system, generator core monitor, and gas control system.

7.4.1 Stator Water Cooling System

Large modern generators usually use water to cool the stator because of the large heat load. The stator winding consists of bars that are made up of hollow strands. Cooling water flows in the strands. Deionized water is used because it has low electrical conductivity and causes less corrosion than ordinary water. The deionized water is cooled in heat exchangers by a service water system. There is also a continuous flow through a bypass line with a deionizer to maintain purity of the water.

7.4.2 Hydrogen Cooling System

The rotor and some parts of the stator are cooled by hydrogen. A fan on each end of the rotor circulates the hydrogen, and external coolers are used to remove heat. Hydrogen is used because of its low density and high thermal conductivity, and it will not cause oxidation. Low density will minimize windage loss. The major problem with hydrogen is the danger of explosion if it is mixed with air. If the hydrogen is between 4.1% and 74.2% of the mixture, it will burn or explode. The hydrogen purity is usually greater than 97% for safety and efficiency of cooling.

7.4.3 Generator Core Monitor

A core monitor is provided to sense a breakdown of insulation in the generator. Hydrogen flows into the system from a high pressure point and returns to a low pressure point. It flows through a tube containing an alpha source and a pair of electrodes. The alpha particles ionize the hydrogen gas causing a current in the circuit connected to the electrode. When insulation breaks down, small particles of the insulation flow through the detector with the hydrogen and attract ions and cause a decrease in the current.

7.4.4 Gas Control System

To allow the generator to be opened to the atmosphere without having an explosive mixture of hydrogen and air, a gas control system is provided. The system will purge the hydrogen out with carbon dioxide. Then the carbon dioxide is purged with air. The process is reversed to restore hydrogen to the generator to resume operation.

7.4.5 Hydrogen Seal Oil System

The hydrogen seal oil system is designed to prevent hydrogen from leaking out of the generator where the shaft penetrates the housing. In one system design, the seal oil is supplied to a single ring around the shaft and the oil flows in both directions. The oil that flows toward the inside of the generator will carry off some hydrogen that will be removed in the hydrogen removal section. The remainder of the oil flows toward the outside of the generator and picks up some air which is removed in the air removal section by venting. Another system design has a hydrogen side supply of oil and an air side supply of oil, but the basic operation of the systems is similar. Hydrogen is kept from leaking out and air is kept from mixing with the hydrogen.

7.5 Generator Operation

Two parameters together describe generator output: frequency and terminal voltage. Output frequency is normally a direct function of the speed of the prime mover (diesel engine or steam turbine). Terminal voltage is primarily a function of the magnitude of the voltage induced in the armature by the magnetic field.

One characteristic of an AC generator is its tendency to slow down when a load is applied. As load is applied to a generator, armature current is developed which establishes an armature magnetic field. (Note there are now two magnetic fields: the main field from the current in the rotor field windings and the armature field from the current in the armature windings.) The armature field acts to oppose the direction of rotation of the main field. This opposition is in turn "felt" by the prime mover. Given a generator with a constant motive force applied by the prime mover, the generator will exhibit a decrease in speed from a no-load condition to a full load condition dependent on the magnitude of the armature current. This reduction in speed causes a corresponding reduction in output frequency.

As electric load is added to an AC generator, the output voltage also tends to decrease. As the load is increased, armature current is increased, which has two effects. First, there is an increased voltage drop due to the resistance in the armature (E=IR). A more significant effect is the result of the interaction of the armature field with the main rotor field. This interaction is called armature reaction. The phase relationship of the armature field to the main rotor field is primarily determined by the load. If the load is capacitive, the phase relationship of the armature and rotor fields will be such that the armature field strengthens the rotor field and the voltage induced in the armature (and the terminal voltage) will be higher. If the load is inductive, the armature field will weaken the rotor field and the induced voltage (and terminal voltage) will be lower. Loads are typically inductive; therefore, for a given magnitude of excitation, a generator will exhibit a decrease in output voltage from a no-load to full load condition.

7.5.1 Speed and Voltage Regulation

Large power generators have both speed and voltage regulators that operate to adjust the motive force (steam to the turbine or fuel to the diesel) and the excitation or rotor field strength. The speed regulator or speed governor can best be understood by considering a turbine driven generator supplying an isolated load system. Without a speed regulator, the prime mover speed (and generator frequency) would drop off rapidly with an increase in load. The speed regulator senses the tendency for the prime mover to slow down with increased load and sends a signal to the governor to increase speed. The resultant characteristic of generator frequency versus real load (watts) is referred to as the speed droop of the system and is illustrated in Figure 7-9A. In practice, speed regulation may result in about a 3% drop in frequency from no load to full load. For a 60 Hz generator, this corresponds to about a 1.8 Hz drop between no load and full load. Although the speed droop characteristic was described using an isolated load system, the speed droop characteristic is primarily needed to operate generators in parallel.

When a generator is supplying current to a load system that is isolated from other generators, it may be desirable to operate the generator at constant speed for all system loads, or in isochronous operation. For isochronous operations the speed regulator senses any tendency of the generator to slow down under increased load and sends an increase-speed signal to the governor to maintain the set constant speed. If the load is decreased, causing the generator to tend to speed up, a decrease-speed signal is sent to the governor to maintain the desired constant speed.

Generator voltage regulators control field excitation(field current) in response to changes in reactive load in a manner similar to the way the speed regulator controls the governor in response to changes in real load. The voltage regulator is sensitive to the phase relationship between terminal voltage and armature current and acts to maintain terminal voltage constant for changes in real load. Increases in inductive reactive load, on the other hand, result in a linear decrease in terminal voltage in the case of an isolated generator as is shown by the characteristic in Figure 7-9B. Increase in reactive load does not affect generator frequency. Voltage regulators for large power generators typically have both a manual and automatic mode of operation. In the manual mode, operator action is required to maintain the desired output by adjusting the entire characteristic upward in response to an increase in reactive load. In the automatic mode, this adjustment is done automatically by the regulator.

7.5.2 Single Generator Supplying an Isolated Load

Figure 7-10A depicts the situation of a wye connected generator operating with a 0.83 lagging power factor and supplying 4160 volts, 60 Hz to two isolated, delta connected loads. The loads are said to be isolated because there is only a single generator supplying them. Note from the power triangles of Figure 7-10B that the real and reactive loads supplied by the generator are simply the sum of the real and reactive loads associated with load 1 and load 2. Note also that the negative (capacitive) reactive power associated with load 2 cancels out some of the positive (inductive) reactive power associated with load 1. Thus it can be seen that for the situation shown in Figure 7-10A and 7-10B and *for single generators supplying isolated loads in general, the power factor of the generator is determined by the loads*. If a third, purely resistive load were added to this system, the total power supplied by the generator would increase, the reactive power would remain the same; therefore, the power factor of the generator would increase. This power factor is shown as:

$$\text{pf} = \cos\left[\tan^{-1}\left[\frac{\text{reactive power}}{\text{real power}}\right]\right]$$

In Figure 7-10C, the relationship between the generator real and reactive loads and the generator frequency and voltage is shown for the above example. The operating frequency of 60 Hz is a function of:

- The no-load frequency setpoint of the speed regulator,
- The speed regulator characteristic (speed droop), and
- The real power supplied by the generator (2200 kW).

Similarly, the operating voltage of 4160 volts is determined by:

- The no-load voltage setpoint of the voltage regulator,
- The voltage regulator characteristic (voltage droop), and
- The reactive power supplied by the generator (1484 kVAR).

To increase the frequency from 60 Hz to 60.1 Hz, for example, the no-load frequency setpoint of the speed regulator would have to be adjusted by an operator to increase the prime mover's governor setting and raise the entire regulator characteristic curve upward. To raise the operating voltage, the no-load voltage setpoint would have to be raised by an operator. That in turn causes increased generator excitation current for all reactive loads. This is illustrated in Figure 7-11.

The emergency diesel generator is unique in that its speed regulator has two modes of operation. If the generator is supplying isolated loads, the speed droop is set to zero. In other words, the regulator maintains frequency at 60 Hz for all rated loads. If the generator is to be operated in parallel with other generators, its speed droop is set so that speed drops off as load is increased. Typically this amounts to about a 5% decrease in speed between no load and full load.

7.5.3 The Infinite Bus

Very large power systems made up of many generators connected in parallel do not exhibit any noticeable decrease in frequency or voltage with increases of real or reactive load. Because any single generator or load is very small compared to this network, the network is referred to as an <u>infinite bus</u> or grid and has the frequency and voltage characteristics shown in Figure 7-12. Any load or generator connected to an infinite bus will operate at the frequency and voltage of the bus.

Figure 7-13 depicts a generator in parallel with an infinite bus and supplying 7000 MW at 0.81 lagging power factor. The bus voltage is 22 kV and bus frequency is 60 Hz. Therefore, generator 1 operates at 22 kV and 60 Hz. As with the case of a single generator supplying an isolated load, the power factor of generator 1 is determined by the loads it is supplying. This can be seen from the power triangle in the lower portion of Figure 7-13. However, *unlike that case of a single generator supplying isolated loads*, the real power and reactive power supplied by generator 1 do not equal the real power and reactive power of the load. In this case, each generator connected to the grid is supplying some fraction of the total load's power and reactive power. So the question is, how are the real and reactive loads of generator 1 determined and controlled?

The answer to that question is illustrated in Figure 7-14 which depicts the load sharing between a generator and an infinite bus. The shaded area represents the real power and reactive power being supplied by generator 1. If the no-load frequency of the speed regulator is adjusted upward to open the turbine governor and to supply more steam to the turbine, it will not turn faster because its speed is dictated by the infinite bus. However, it will supply a greater fraction of the real load and that is illustrated by the dotted lines on the frequency versus real power diagram of Figure 7-14. Similarly, adjusting the no-load voltage setpoint of the voltage regulator upward by increasing excitation current will not change generated voltage, but rather it will increase the reactive load supplied by the generator.

Note then, that by adjusting the speed regulator and voltage regulator of a generator in parallel with an infinite bus, *we can control the real and reactive power supplied by the generator, and, therefore, its power factor*. If, in Figure 7-14, the excitation only were increased (and the speed regulator unchanged), generator 1 would supply more reactive power, its power triangle would change shape (same real power, more reactive power), and the power factor of the generator would become more lagging. Remember that even though the power factor of generator 1 changed, the power factor of the grid is determined by the loads on the grid, and they did not change. Therefore, when generator 1 supplies more of the reactive load, the other generators on the grid must together supply that much less. Because the grid is large compared to any one generator, the change in one generator loading has a very small impact.

Under normal conditions, the voltage regulator is adjusted such that the no-load voltage is above the system voltage. Induced voltage in the armature is higher than terminal voltage and reactive current will flow from the generator to the grid. The generator is described as being overexcited in this condition. VARs are said to be positive (flowing out) in this case and the generator is operating with a lagging power factor.

Under unusual conditions, the voltage regulator is adjusted such that the no-load voltage is below the system voltage. Reactive current will flow from the grid to the armature. VARs are negative (flowing in), the generator is described as underexcited, and operating with a leading power factor.

7.5.4 Paralleling Generators

Three conditions must be met to parallel a generator to an operating grid. First, *oncoming generator voltage must match grid voltage.* This minimizes the potential difference across the breaker and minimizes arcing that would otherwise occur if the breaker was shut across a high potential. The second condition is that *oncoming generator frequency must be slightly higher (a fraction of a hertz) than grid frequency.* This ensures that when the generator output breaker is shut, the generator will immediately pick up some real load when it slows down. This requirement is illustrated in Figure 7-15. By ensuring that the generator immediately picks up real load, the possibility of motorizing the generator is minimized.

The final paralleling requirement is that *the generator output breaker be shut when the generator output is in phase with the grid.* Again, this minimizes the potential difference across the output breaker.

An instrument called a synchroscope, illustrated in Figure 7-16, is used to compare the voltage phase relationship and relative frequencies of the two AC systems. The synchroscope physically measures the voltage potential between a single phase of the incoming bus (normally the generator) and the running bus (the portion of the system that is already connected to a power source). Rotation in the *FAST* (clockwise) direction indicates the incoming (generator) frequency is "faster" than the frequency on the running bus. Similarly, rotation in the *SLOW* direction indicates the incoming (generator) frequency is "slower" than the running bus frequency. The speed of the pointer rotation indicates the magnitude of the difference in frequencies. The angular position of the pointer at any instant indicates the magnitude of the phase difference at that instant. When the pointer is at 6 o'clock, the two systems are 180° out of phase. When the pointer is at 12 o'clock, the systems are in phase.

The procedure to parallel a generator to an infinite bus first requires that the incoming generator voltage be adjusted to match the running voltage. Next, the generator speed is adjusted so that the synchroscope turns slowly in the *FAST* direction, indicating that incoming frequency is slightly higher than the running frequency. Finally, the generator breaker is shut when the synchroscope pointer is at the 12 o'clock position, indicating that the two systems are in phase.

7.6 Generator Limitations

Figure 7-17 illustrates four conditions or quadrants in which generator operation may theoretically occur. Regions II and III represent negative power or motoring of the generator and is prevented by protective devices. Regions I and IV have the generator supplying real power to the grid, with the difference between the regions being reactive power. In Region I, the reactive power is said to be outgoing (positive), lagging, or inductive. Inductive means that the loads being supplied are inductors; that is, they require additional current to produce their magnetic fields. Motors are an example of this type of load. Lagging means that the current is behind the voltage in time. Outgoing refers to the fact that there is reactive power going out to the loads. Most operation is in this region because the grid load tends to be inductive overall.

Region IV is the area of incoming (negative) reactive power, leading power factor, and capacitive. The generator is a (inductive) reactive load on the grid. Part of the generators magnetic field is supplied by the grid. There may be times when the load dispatcher requires some generator to operate in Region IV.

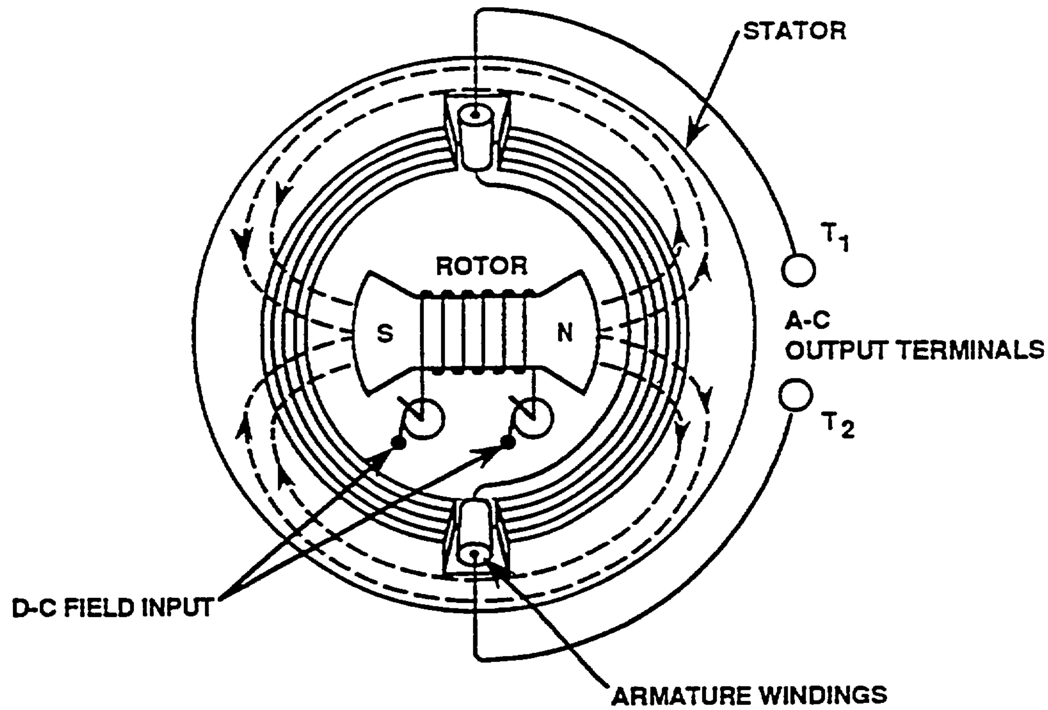
There are limitations on how much reactive power may be supplied or used by the generator, just as there are limitations on the maximum real power produced. Figure 7-18 shows typical generator capability curves.

The limit between points A and B (on a given pressure curve) is the result of *heating in the field coils* due to high current from overexcitation. From points B to C, armature amps are high because of real power supplied. Although stator bars are water cooled, stator punchings are not and rely on hydrogen pressure. Hence, the curve varies according to hydrogen pressure. Line BC exists in both Regions I and IV.

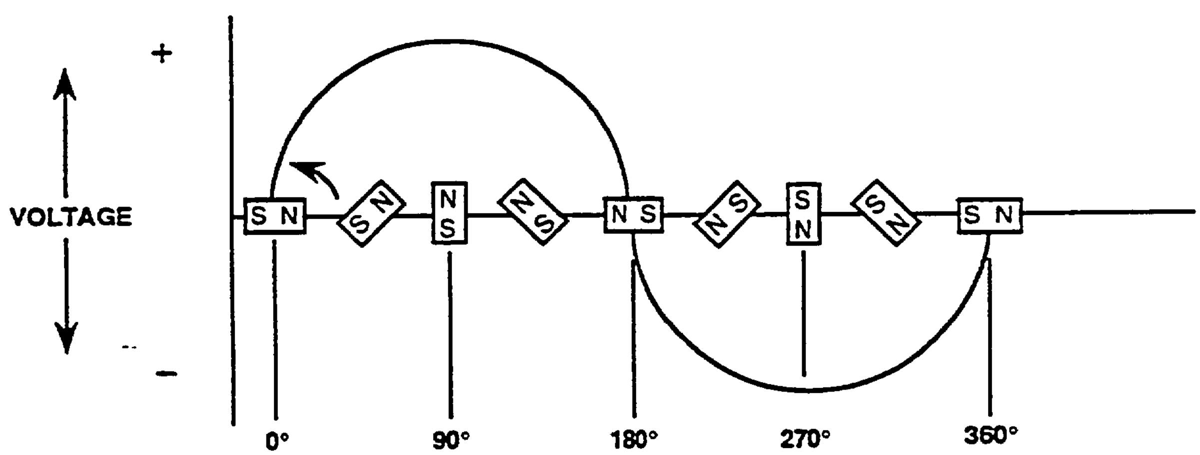
As the grid is required to supply more reactive power to the generator field (points C to D), stator flux distribution becomes more and more uneven. This results in significant differences of potential between laminations of the stator core causing large eddy currents in the stator end punchings. Therefore, the generator is limited by *heating in the armature core ends*. Grid stability limits may be exceeded before reaching this point. Therefore, it is highly unusual that a Load Dispatcher would require generator operation in this region.

Chapter 7 Definitions

FIELD	-	The electrical component of a generator (or motor) that produces the magnetic field.
ARMATURE	-	The electrical component of a generator (or motor) in which the voltage is induced.
STATOR	-	The stationary assembly of electrical components in a generator (or motor).
ROTOR	-	The rotating or moving assembly of electrical components in generator (or motor).

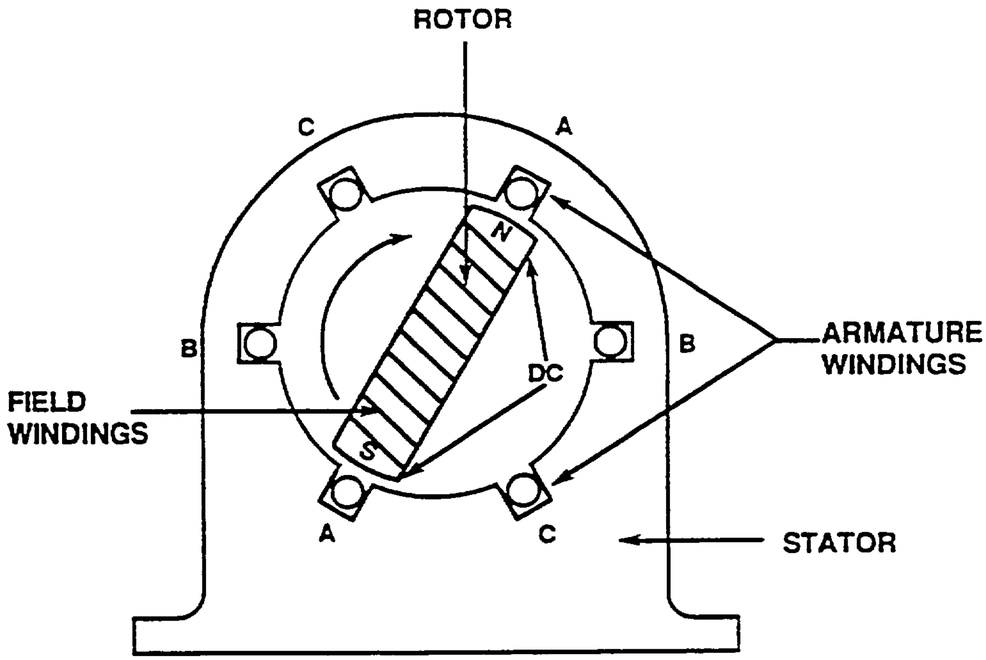


Revolving Field Generator

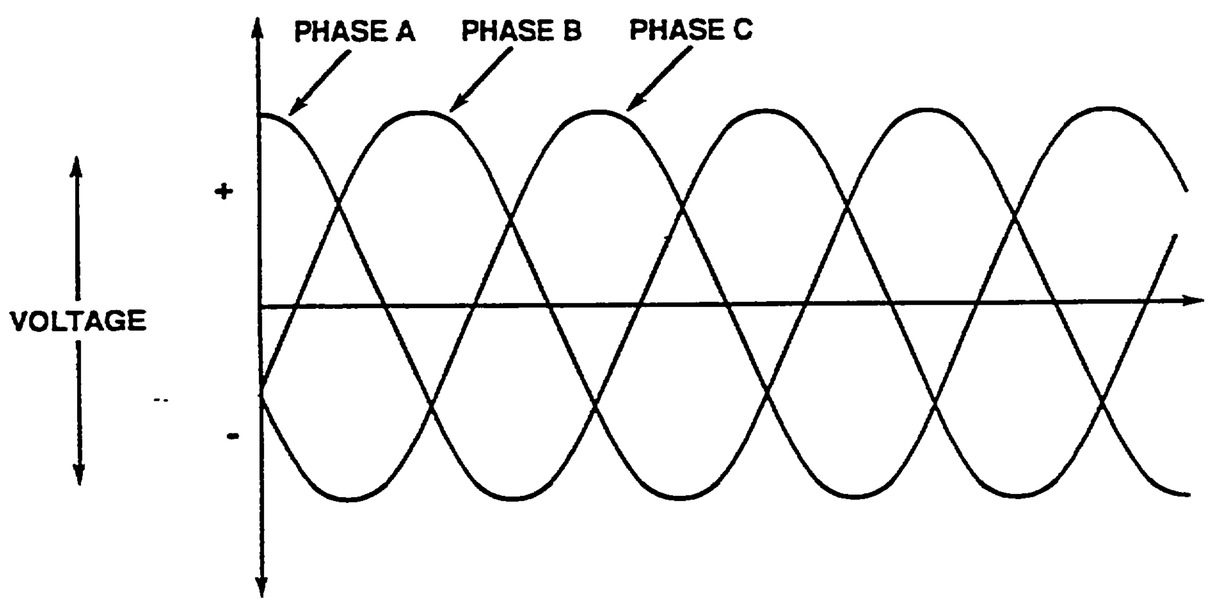


Sine Wave Produced by a Revolving Field A-C Generator

Figure 7 - 1. Revolving Field Generator and Resultant Output



A. Three-Phase AC Generator



B. Sine Wave Produced by Three-Phase Generator

Figure 7-2. Three-Phase Generator and Resultant Output

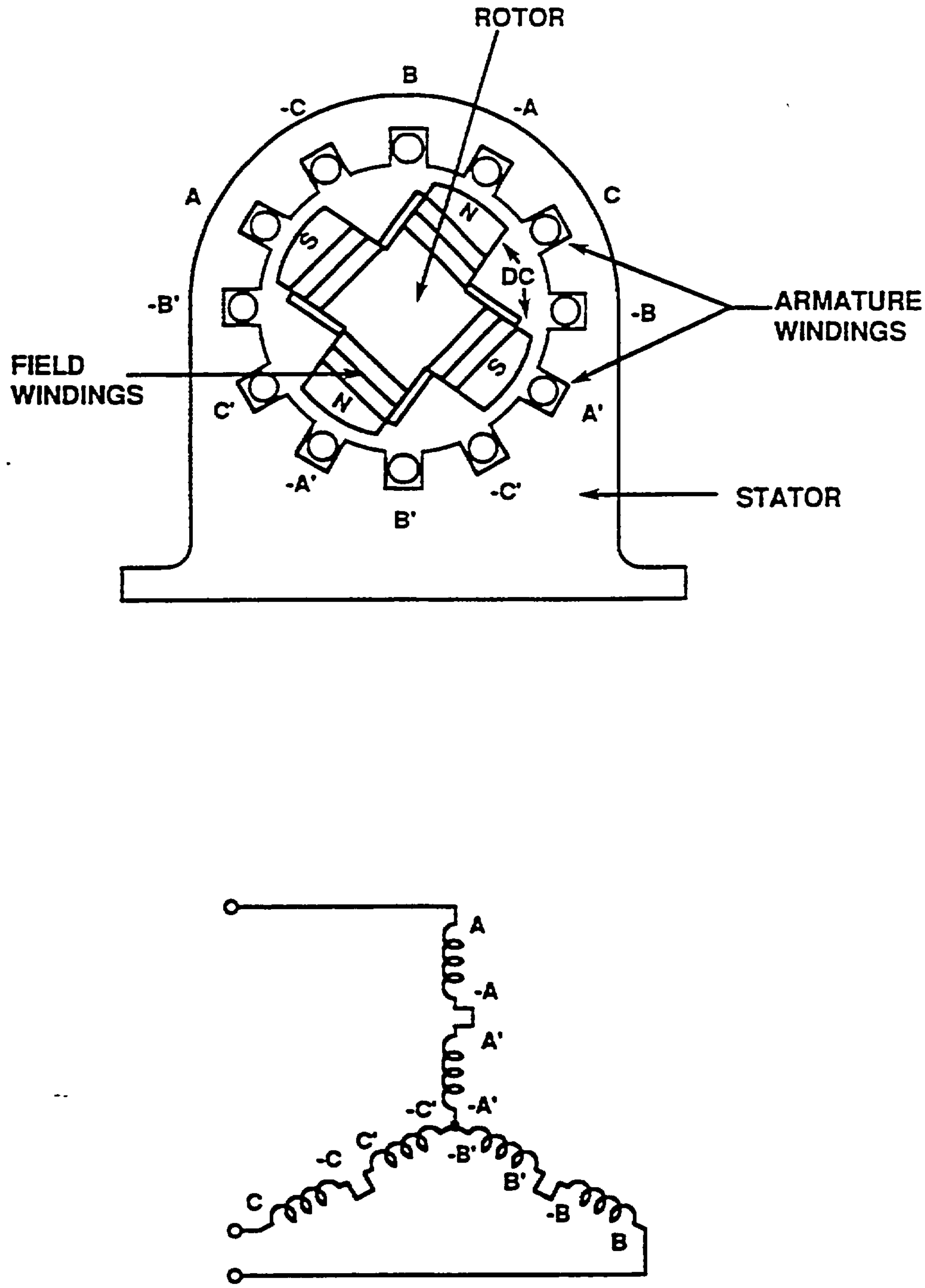


Figure 7-3. Four-Pole, Three-Phase AC Generator and Schematic Diagram for Y-Connected Armature Windings

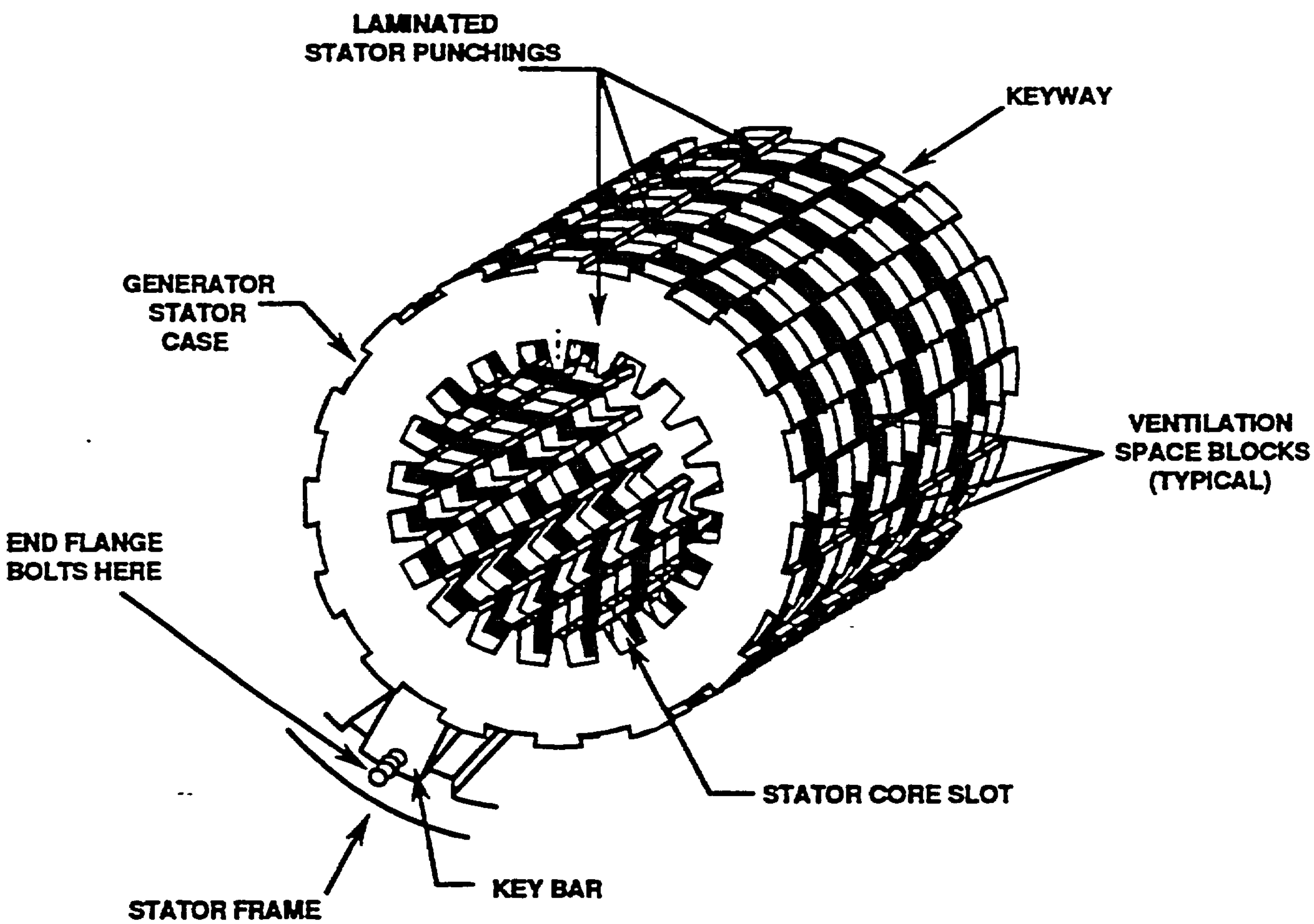


Figure 7-4. Generator Stator or Armature

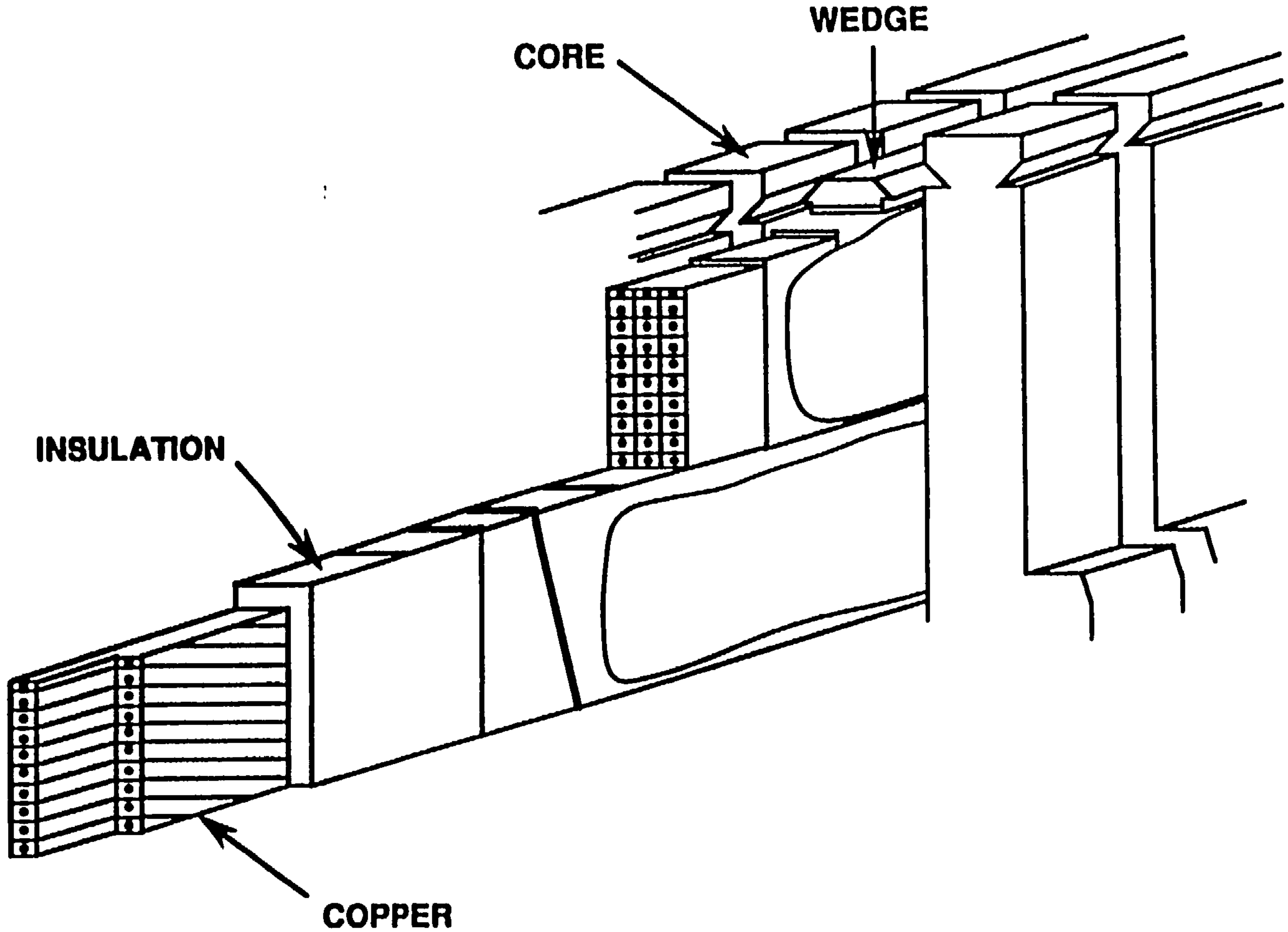


Figure 7-5. Stator Bar Assemblies in Stator Core Slots

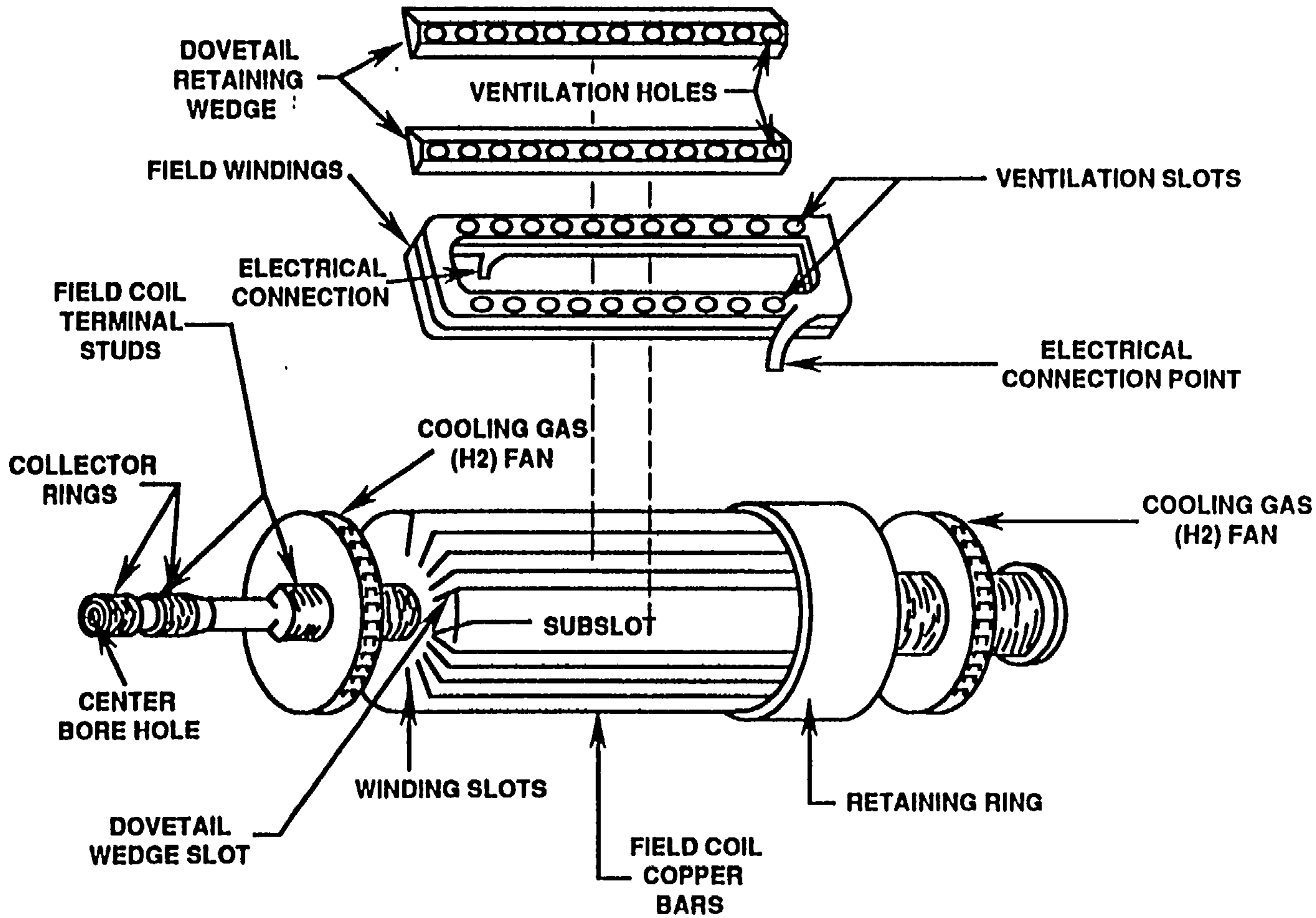


Figure 7-6. Simplified Rotor Assembly

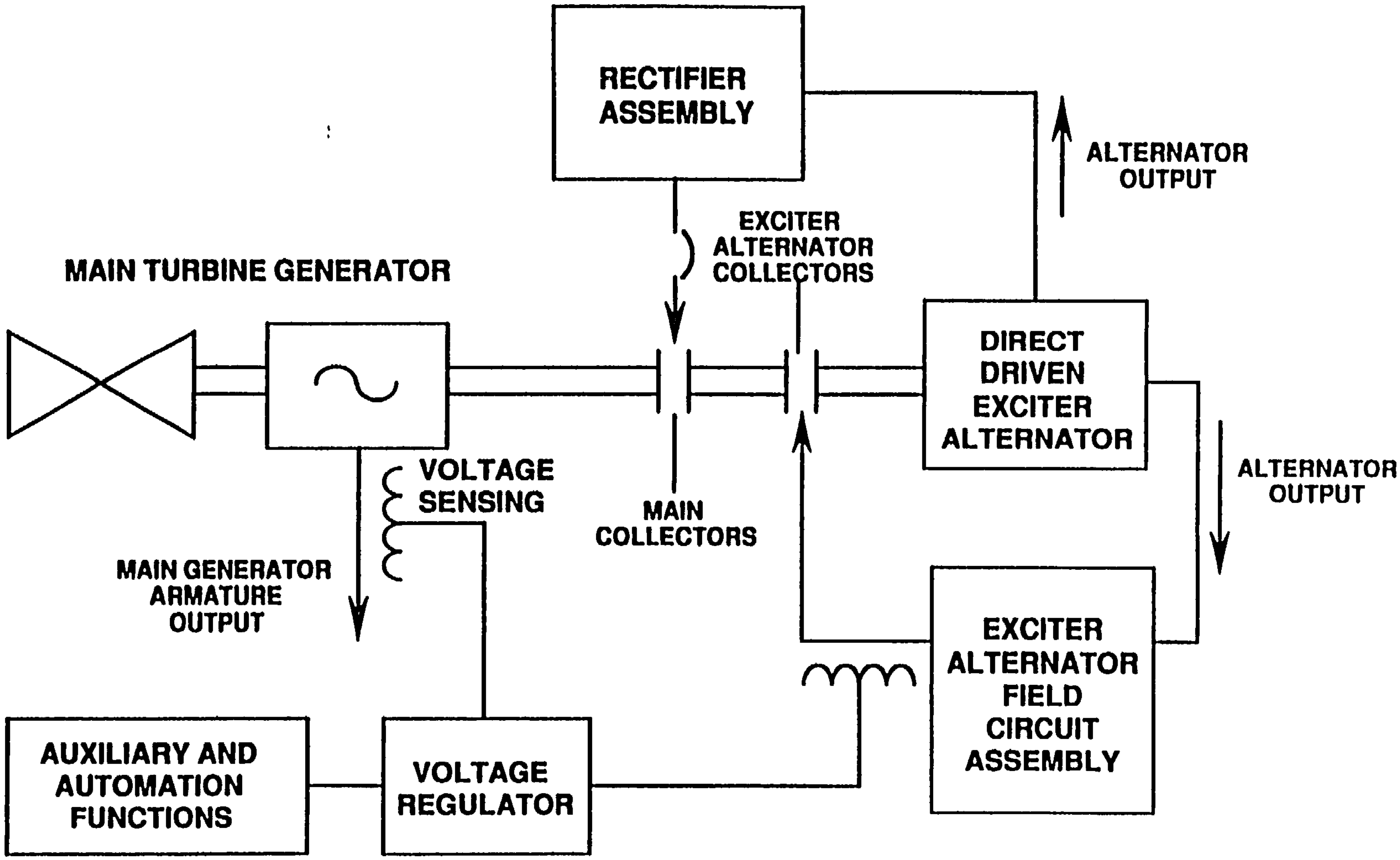


Figure 7-7. Exciter System

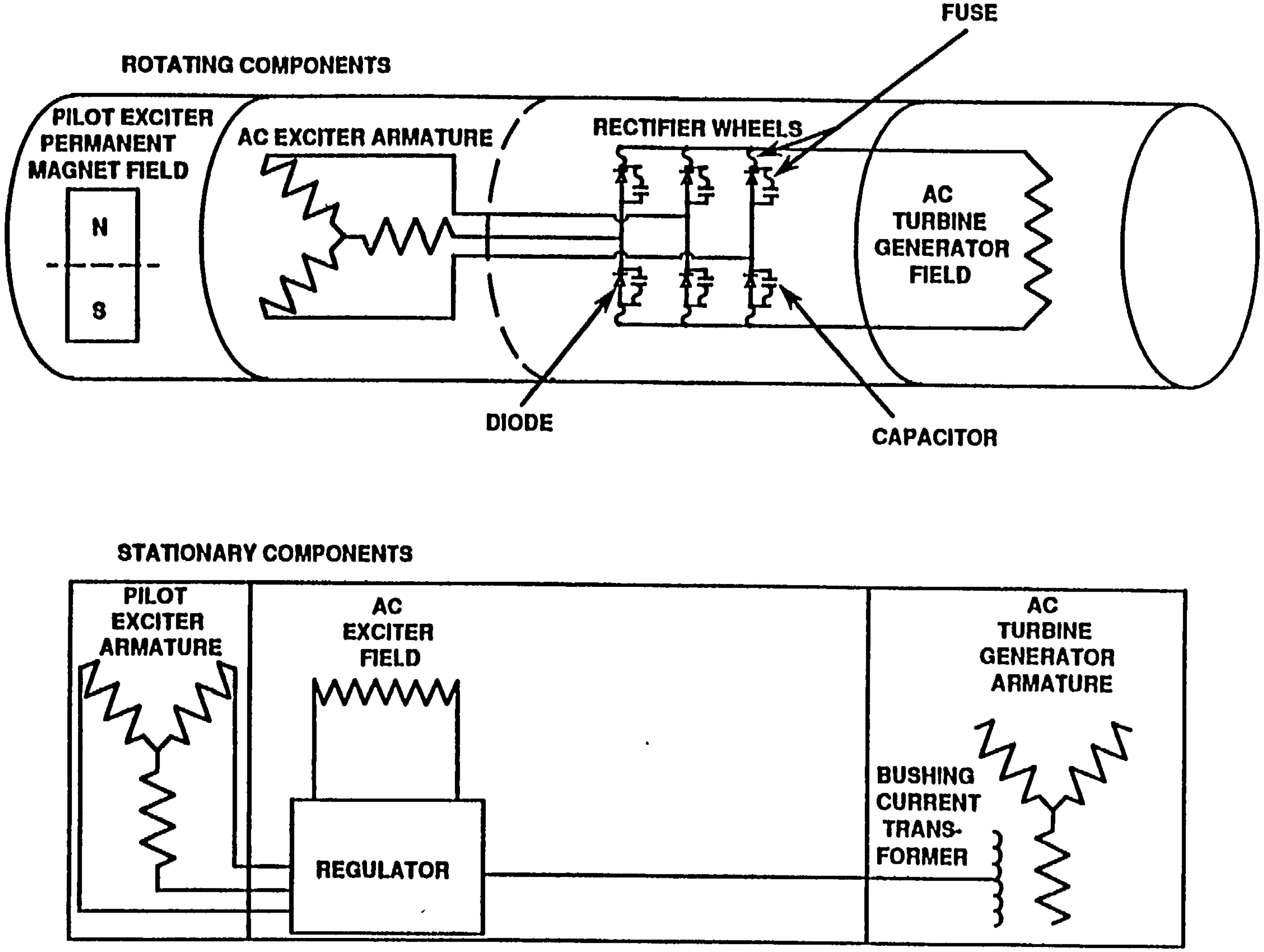


Figure 7-8. Brushless Exciter System

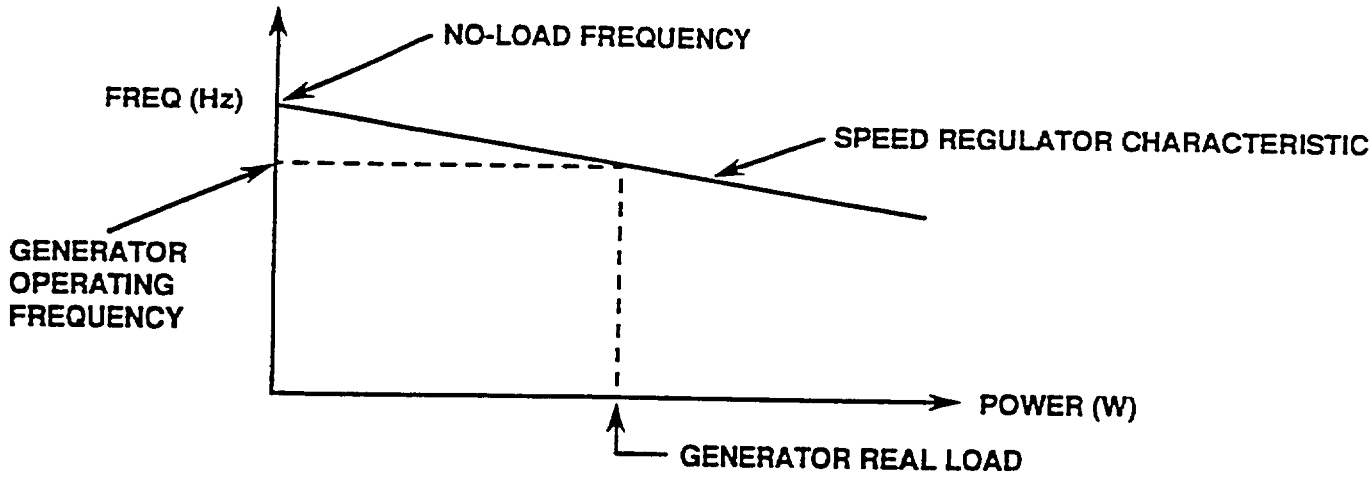


Figure 7-9A. Speed Regulator Characteristic

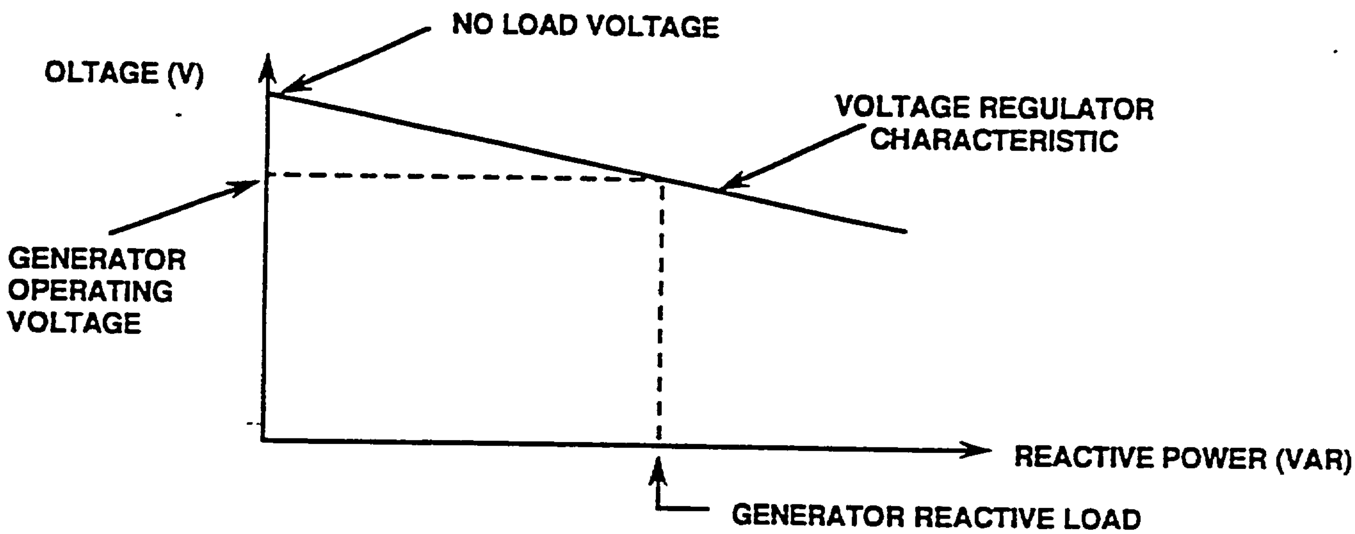


Figure 7-9B. Voltage Regulator Characteristic

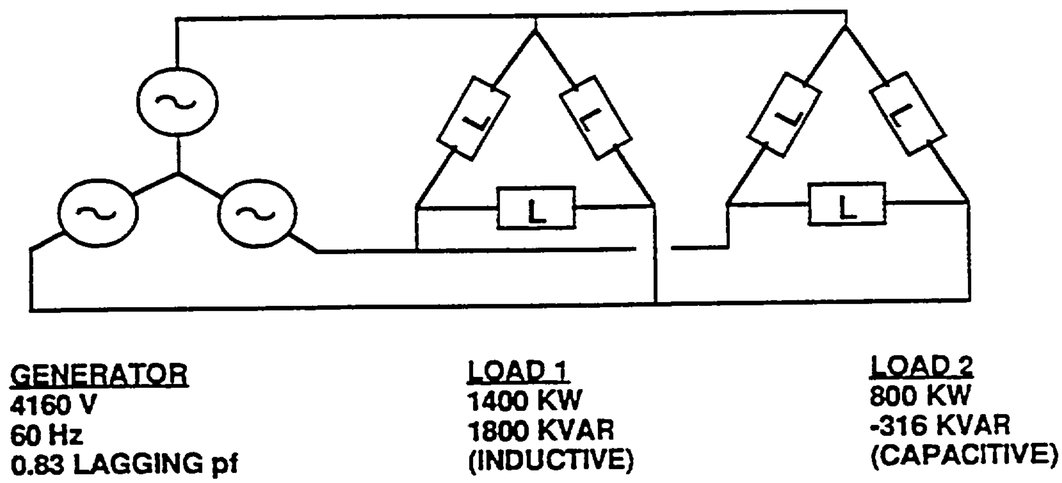


Figure 7-10A. Generator Supplying Isolated Loads

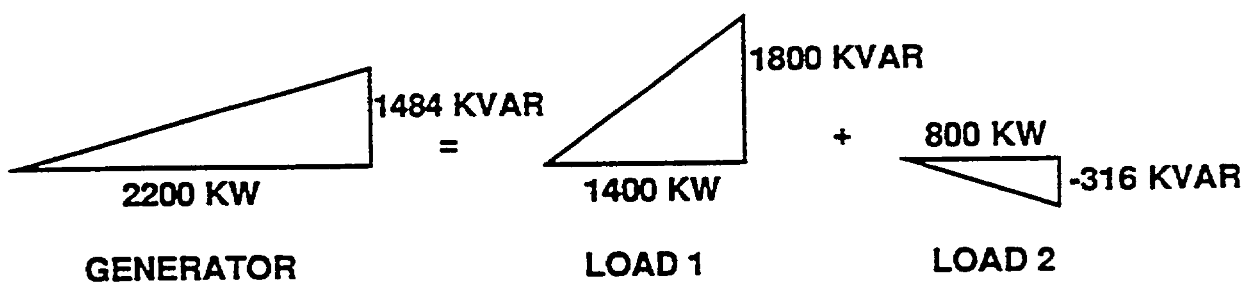


Figure 7-10B. Power Triangles

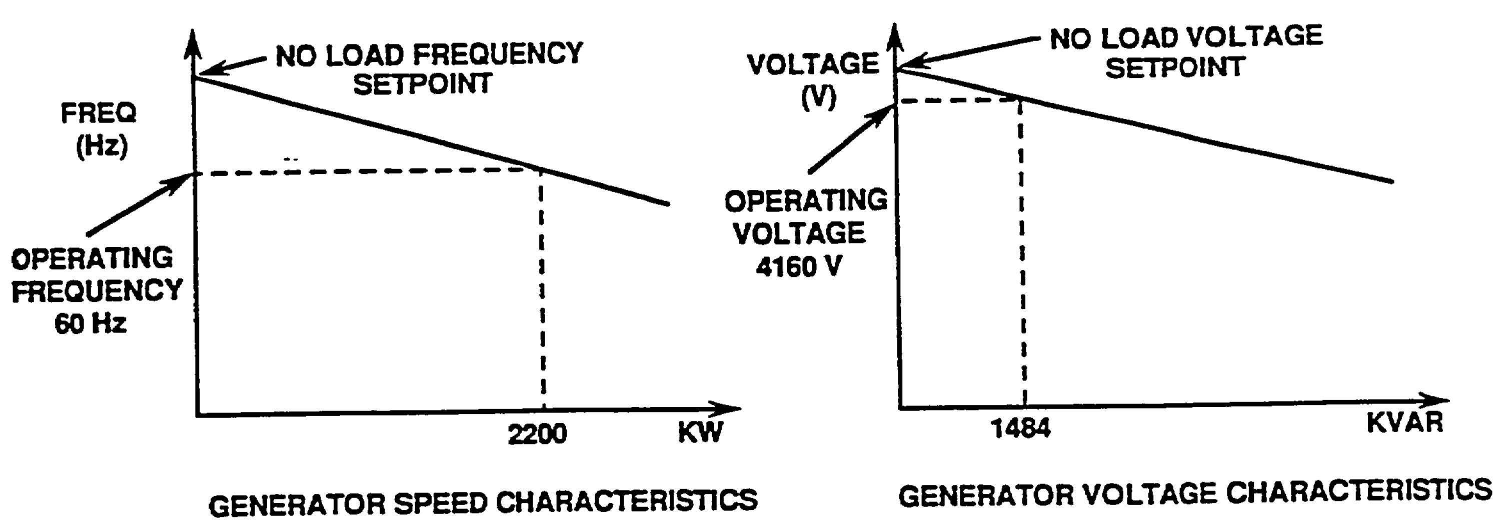


Figure 7-10C. Regulator Characteristic for Generator Supplying Isolated Loads

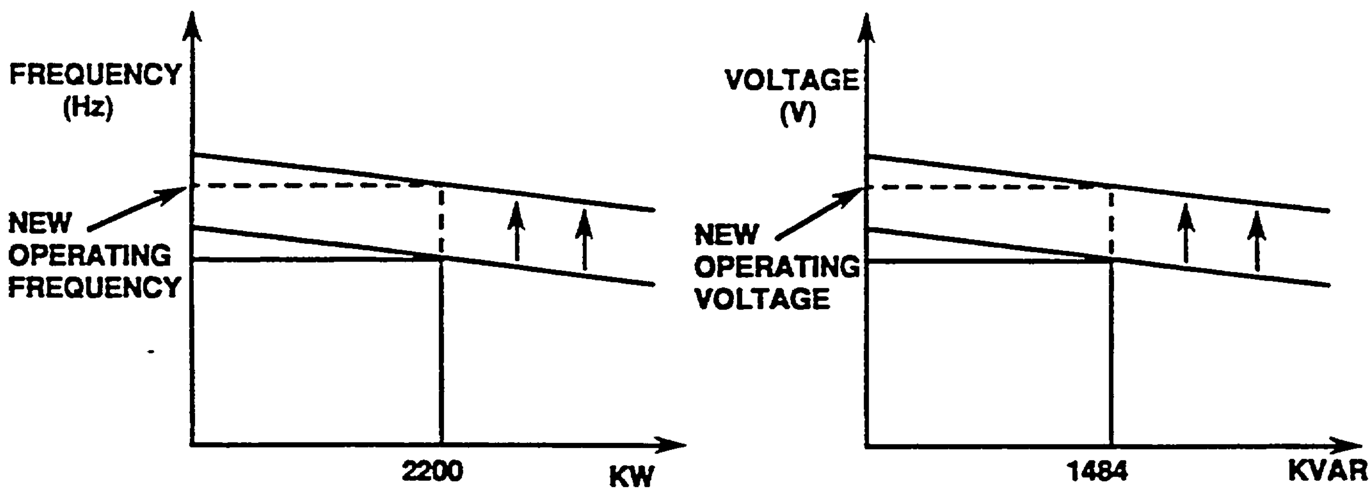


Figure 7-11. Effect of Increasing No-Load Frequency and Voltage Setpoints to Generator Supplying Isolated Loads

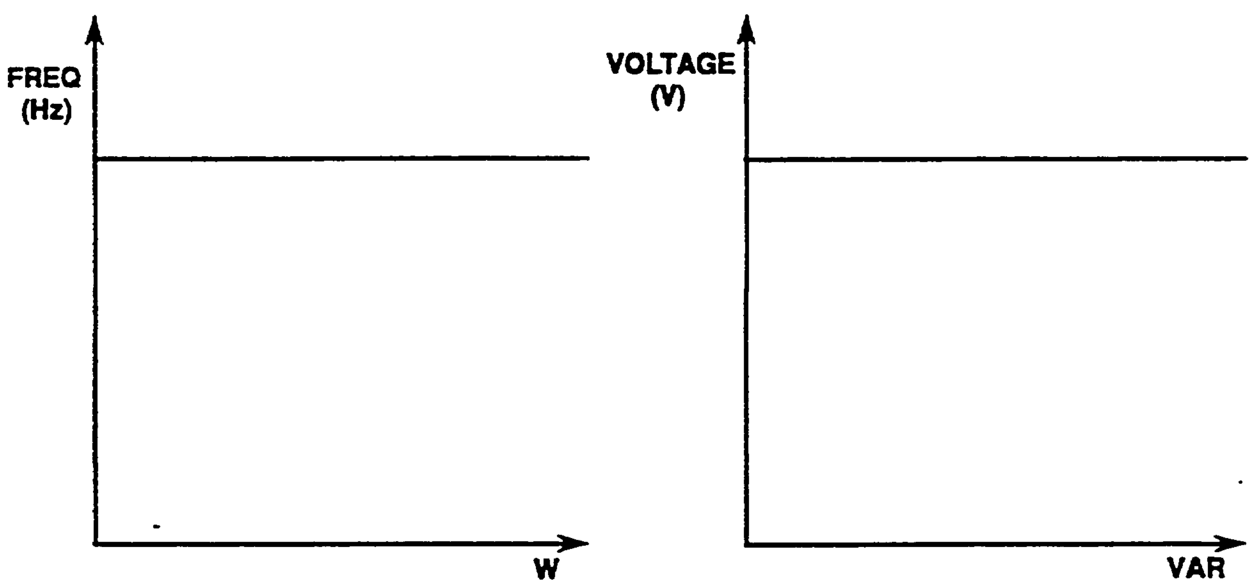


Figure 7-12. Frequency and Voltage Characteristics of an Infinite Bus

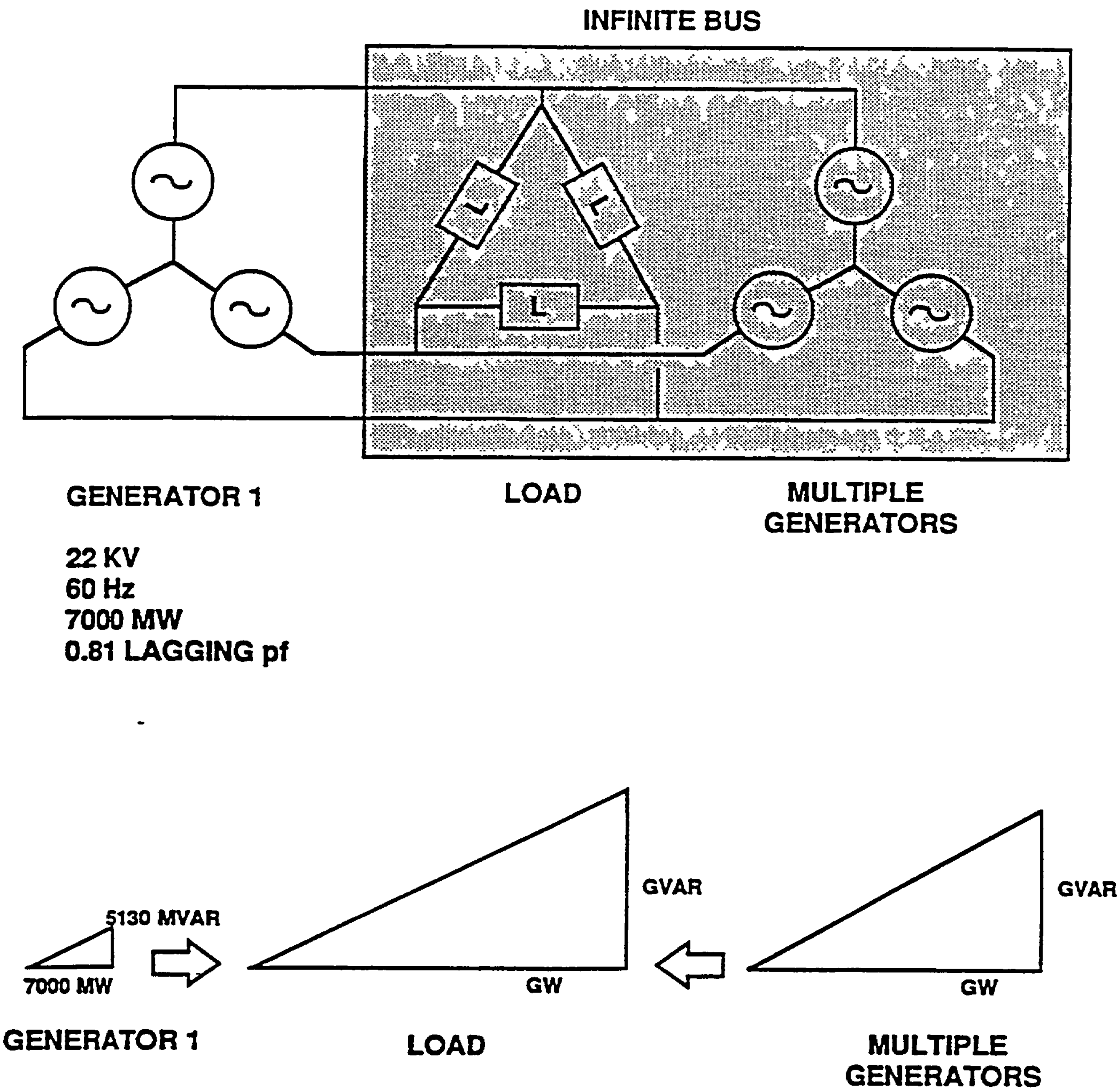


Figure 7-13. Generator in Parallel with an Infinite Bus

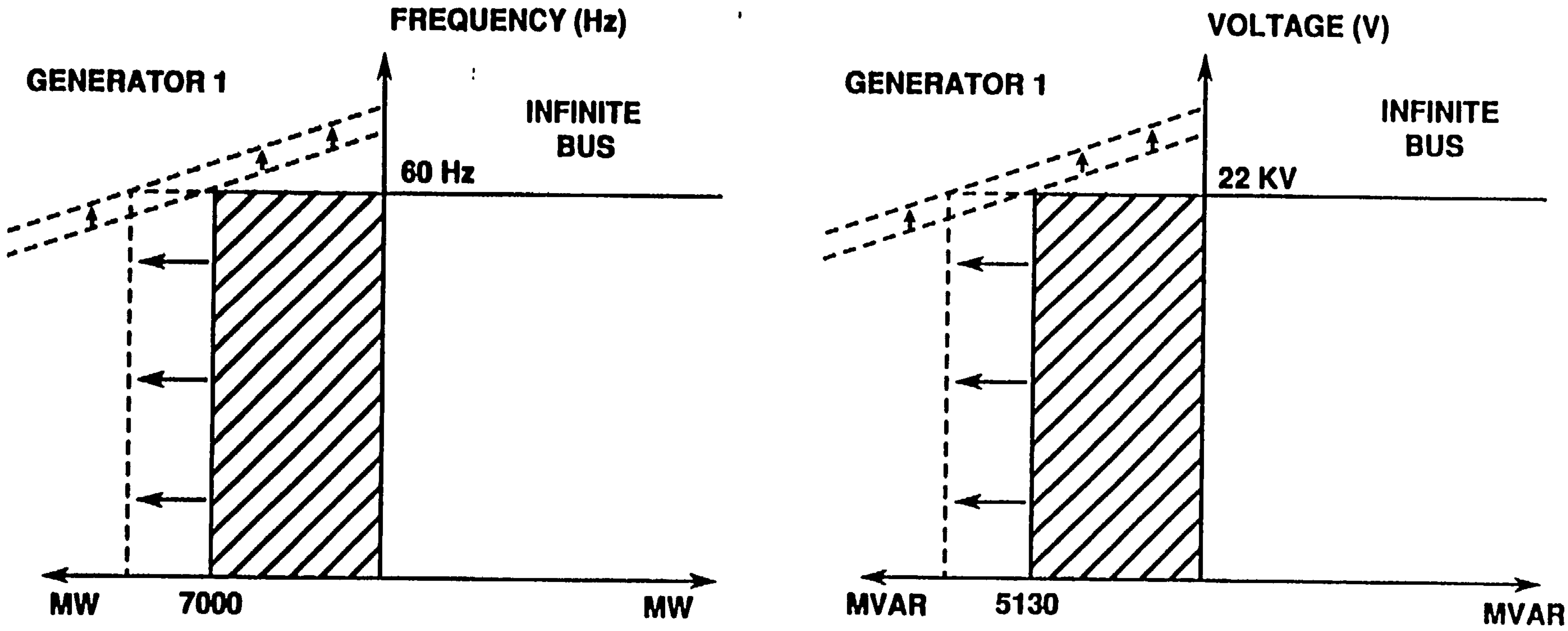


Figure 7-14. Load Sharing Between a Generator and an Infinite Bus

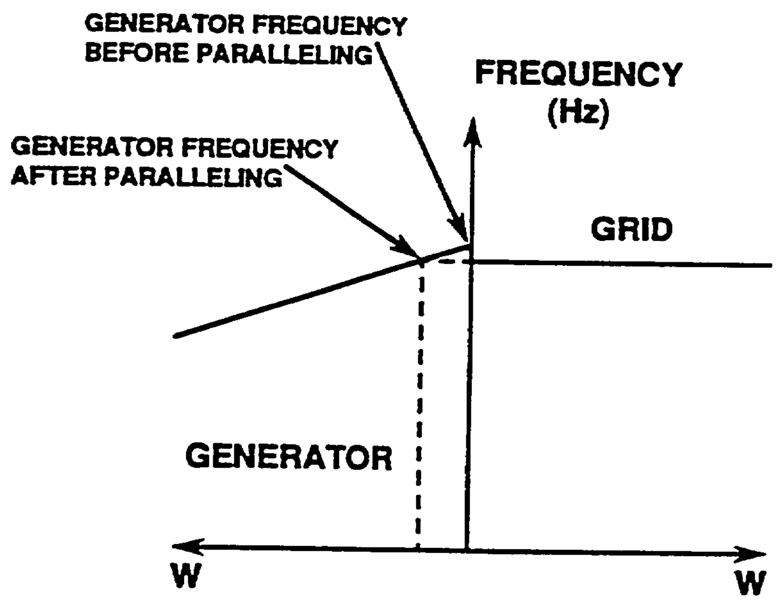


Figure 7-15. Frequency Requirements for Paralleling Generators

Figure 7 - 16. Synchroscope

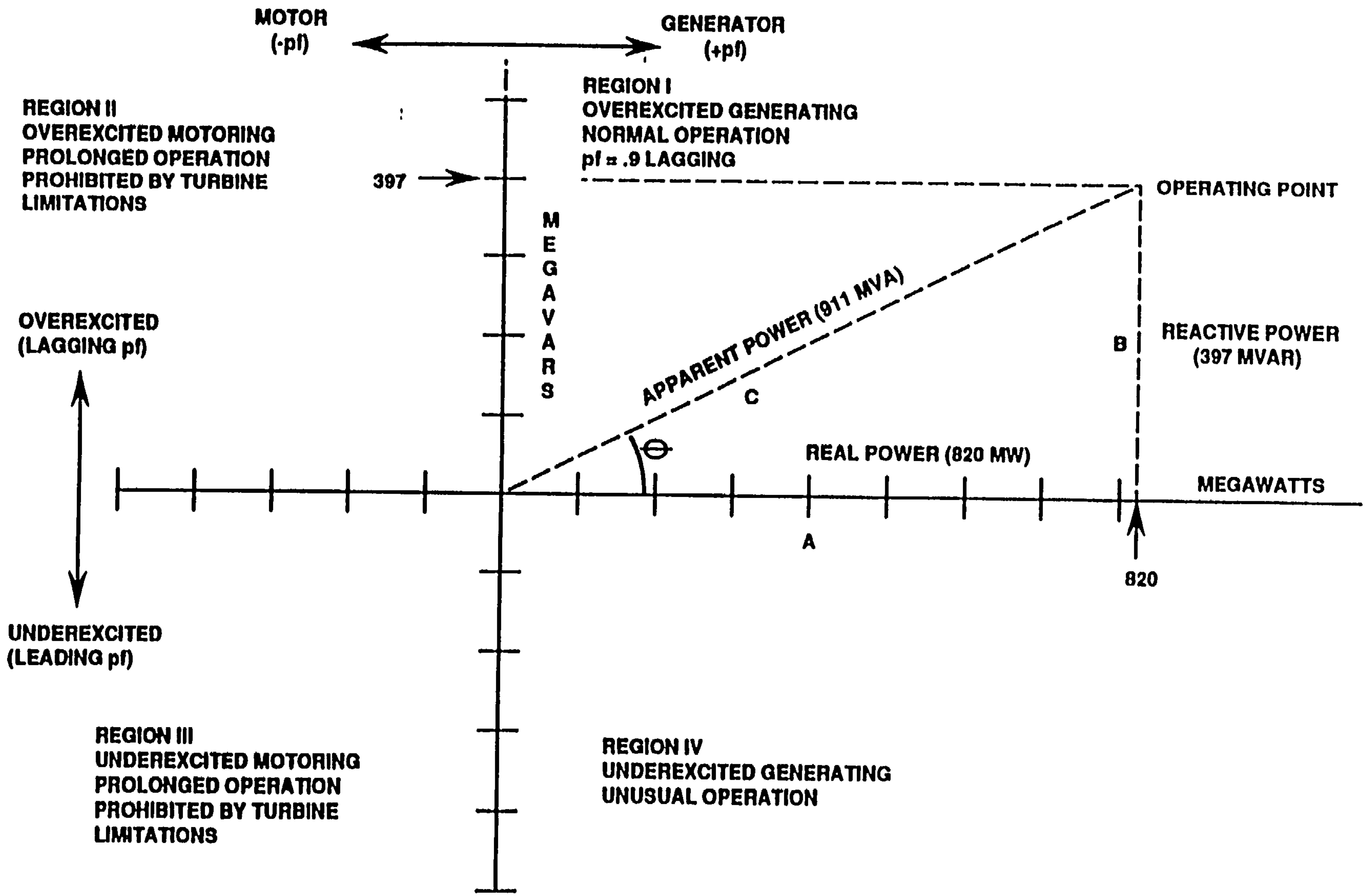
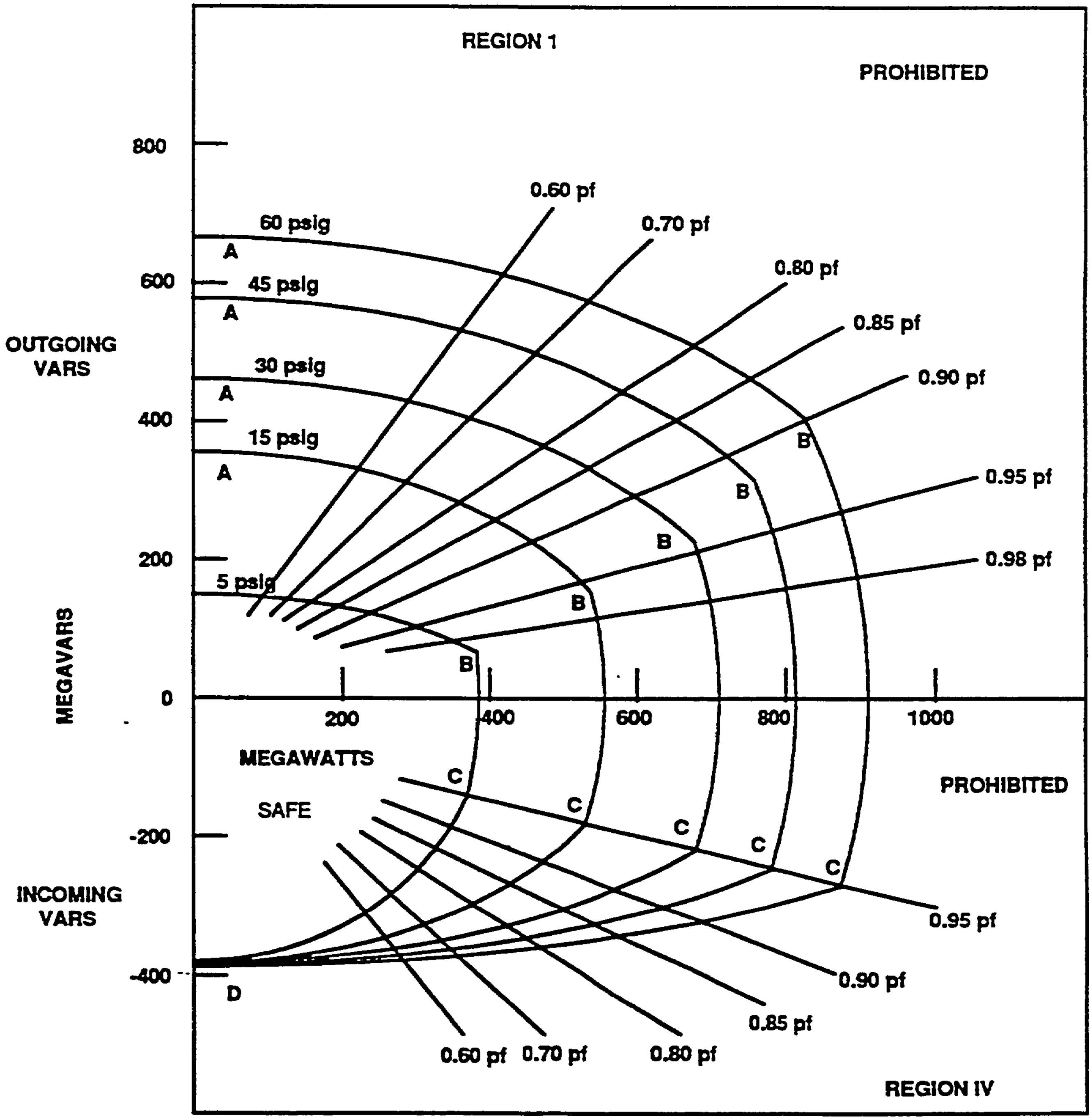


Figure 7-17. Operating Quadrants



CURVE AB LIMITED BY FIELD HEATING
CURVE BC LIMITED BY ARMATURE HEATING
CURVE CD LIMITED BY ARMATURE CORE END HEATING

Figure 7-18. Generator Capability Curves